A Feasibility Study on a Neutrino Source Based on a Muon Storage Ring

MUTAC, Brookhaven, June 15th and 16th

Norbert Holtkamp

- Introduction
- Charge
- Basic Parameters
- Technical Feasibility
- Cost
- Site Dependence

Accelerator Study:

http://www.fnal.gov/projects/muon_collider/nu-factory/

R. Pasquinellis Seven Miracles

Making of the Protons

Making of the Muons

Making of small DE/E

Cooling the Beam

Acceleration

How to handle the Neutrino Radiation

How to Make Useful Physics

The Task

- **A design concept for a muon storage ring and associated support facilities that could, with reasonable assurance, meet performance goals required to support a compelling neutrino based research program.**

- **2.Identification of the likely cost drivers within such a facility.**

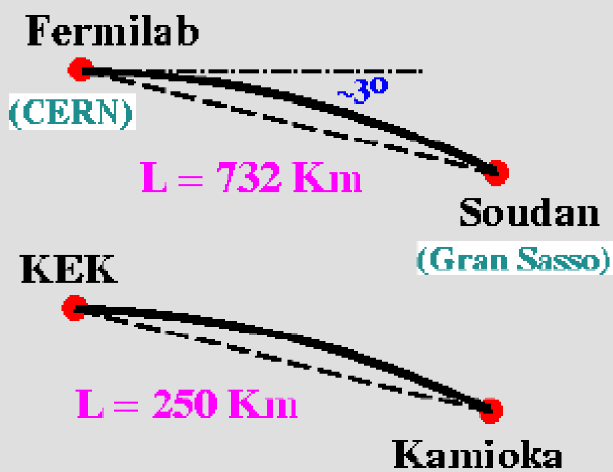
- **3.Identification of an R&D program that would be required to address key areas of technological uncertainty and cost/performance optimization within this design, and that would, upon successful completion, allow one to move with confidence into the conceptual design stage of such a facility.**

- **4.Identification of any specific environmental, safety, and health issues that will require our attention.**

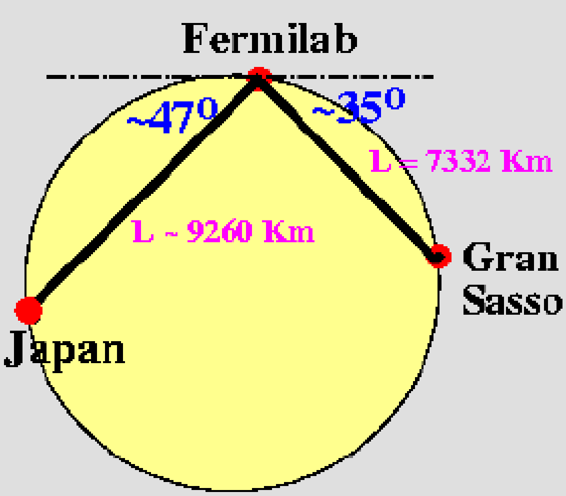
The Energy Choice, the Experiment and the Options

- Choice of baseline beam line angle are connected

	L (km)	Dip (Deg.)	Heading (Deg.)
FNAL –> Soudan	732	3	336
FNAL –> Gran Sasso	7332	35	50
FNAL –> Kamioka	9263	47	325



E_ν (GeV)	L/E (Km/GeV) FNAL–Soudan	L/E (Km/GeV) KEK–Kam.
10	73.2	25.0
20	36.6	12.5
30	24.4	8.3
40	18.3	6.3
50	14.6	5.0



E_ν (GeV)	L/E (Km/GeV) Gran S.	L/E (Km/GeV) Japan
10	~733	~926
20	~367	~463
30	~244	~309
40	~183	~232
50	~145	~185

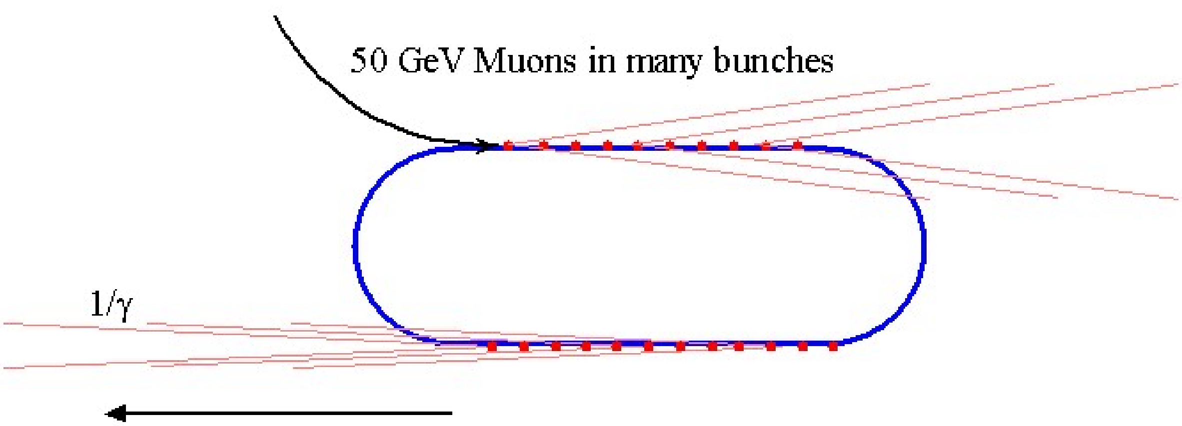
Choice has been made !

Parameters for the Neutrino Source		
- Energy of the ring	**GeV**	**50**
- Number of muons / straight		**2×10^{20}/y** **5×10^{19}/y**
- no polarization		
- capability to switch between μ^+ μ^-		
- FERMI to SLAC / LBNL $\rightarrow$ West Coast		

- Basic Calculation
  - 1/3 of the muons decay in the straight section (39 %)
  - 10 protons for 1 μ into the storage ring (>10; >20-50)
  - 2×10^7 sec
    - 2×10^{13} proton on target per pulse @ 16 GeV and 15 Hz
      - 3×10^{13} proton because of carbon target = 1.5 MW
    - 2×10^{12} μ per pulse to be accelerated and injected into the ring
      - cooling channel ???
    - longer bunch in the proton driver and on target (1 nsec $\rightarrow$ 3)
      - helps
    - ring tilt angle is 13deg (22 %) instead of 35 deg (57 %)
      - ring with these params: not a cost driver at all
      - tilt angle is manageable

The Neutrino Source

- First experiment based on an intense muon source -> does it have to be 50 GeV ??
  - 10 GeV and 50 kT or more magnetized water detector: Goal: Balance detector cost with Accelerator: E*kT*I=const.
  - Start with 2×10^{19}/year (Sessler, Geer) and still good physics ?

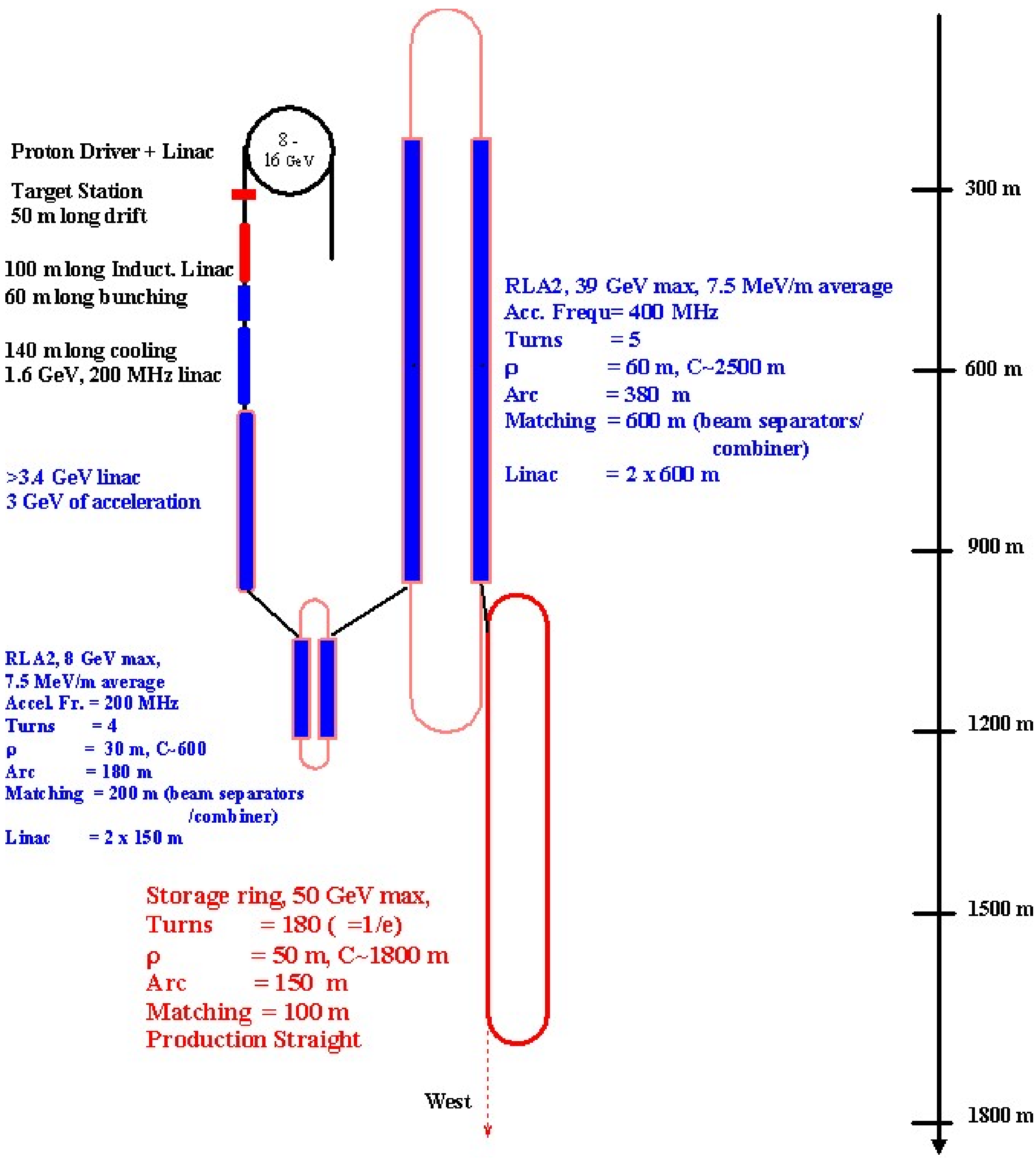


Parameters for the Muon Storage Ring		
Energy	GeV	50
decay ratio	%	>40
Designed for inv. Emittance	m*rad	**0.0032**
Cooling designed for inv. Emitt.	m*rad	**0.0016**
β in straight	m	160
N_μ/pulse	10^{12}	6
typical decay angle of $\mu = 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\varepsilon}/\beta_o) = (\sqrt{\varepsilon}\,\gamma)$	mrad	0.2
Lifetime $c*\gamma*\tau$	m	3×10^5

$\gamma = (1-\alpha^2)/\beta$

Footprint for a 50 GeV Neutrino Source

- Infrastructure is very close together …⇒ It fits under a small site
  - bents between different subssystem is minimized
  - beam loading equal on bot sides of the RLA
- ⇒ Direction of P beam on target defines layout



The Neutrino Source

- Approach:
  - **go more conventional where ever possible**
  - Oak Ridge, FHML, Brookhaven ⇒ the target
    - most people bought the solid target
  - Jefferson Lab / Cornell ⇒ sc rf and re-circulating linacs
    - R&D picked up by NSF and Layout by Jlab
  - LBNL , DUBNA ⇒ induction linacs
    - turned out to be much better than expected, but not cheap
  - IHEP Protvino ⇒ sc solenoid channels
    - so far very good job, but expensive magnet channels even if build in Russia
  - specific design and engineering (cooling channel, target collection, beam manipulation, beam tracking and simulation) → Muon Collider group (12 people @FNAL) + the collaboration
    - (thank Andy for the enormous support)
  - general engineering (large scale rf systems, sc magnets, sc solenoid channels, ps, vacuum, beam lines, tunnel, water) (20 FTE for 6 month)

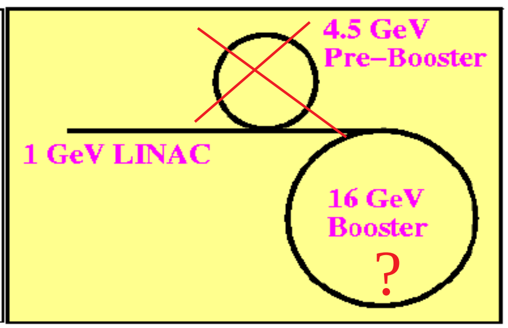
R & D Issues for the Proton Driver Design Study

- **R & D groups (Int. Review April17-18):**
  - **–RF, beam loading, feedback, Collective effects, Magnet, power supplies, vacuum, Lattice, H^- source and linac / linac upgrade, Collaboration with Kek/Japan**

Upgrade 400 MeV Linac –> 1 GeV

Upgrade 8 GeV Booster –> 16 GeV

Add a 4.5 GeV (3 GeV ?) Pre–Booster (facilitates short bunches).

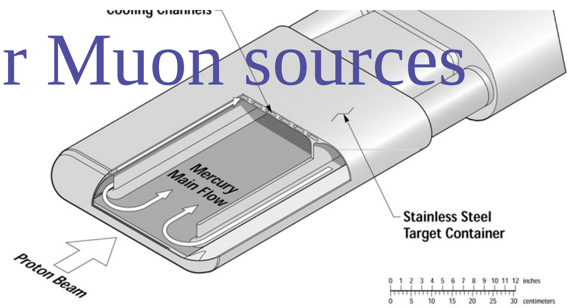


Goal:

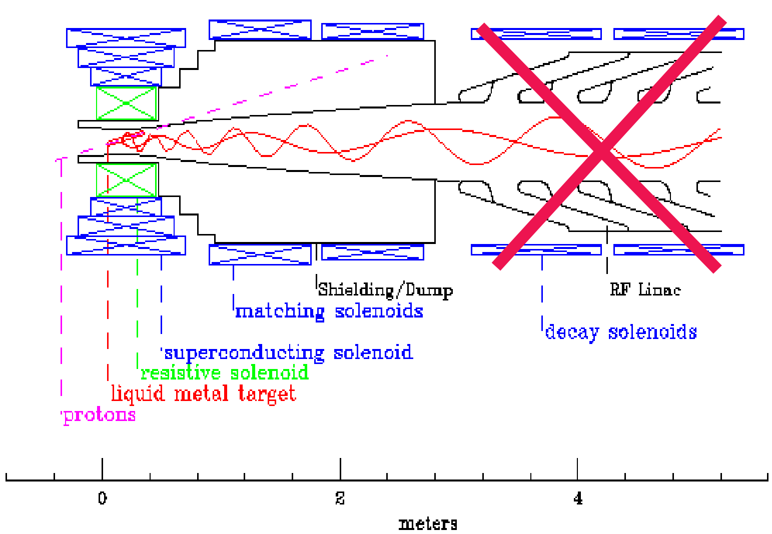
- **$4 \times 0.75 \times 10^{-13} = 3 \times 10^{-13}$ @ 15 Hz**
- **8 GeV versus 16 GeV versus higher energies ?**
- **Achieve 1.5 MW**
- **Number of bunches 4 or more ? Induction Linac**

A Target for the Neutrino Factory

- Comparable Targets:
- RAL: SNS
- CERN/ FNAL: p-Bar
- NSNS Oak Ridge
- NuMI
- for Muon sources



- MC Target Experiment



- The power deposition

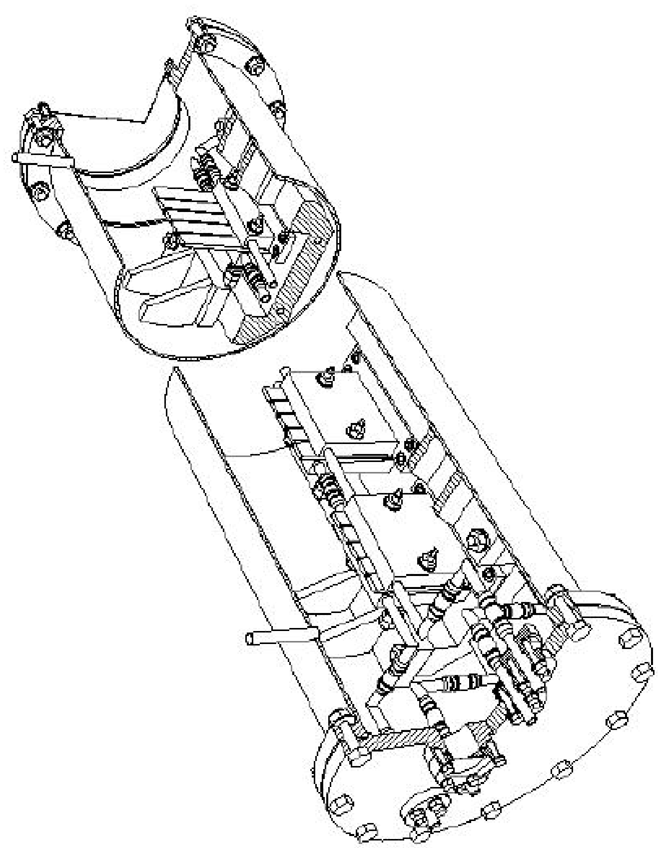


Figure 1.16: Perspective view of the target design.

Make the Target as Simple as Possible

P. Spampinato

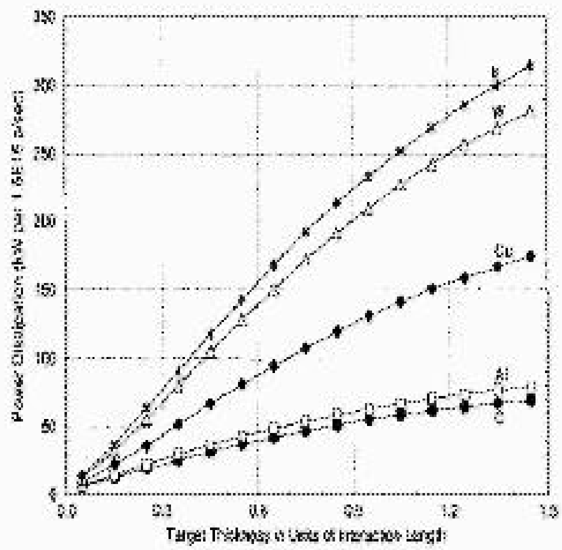
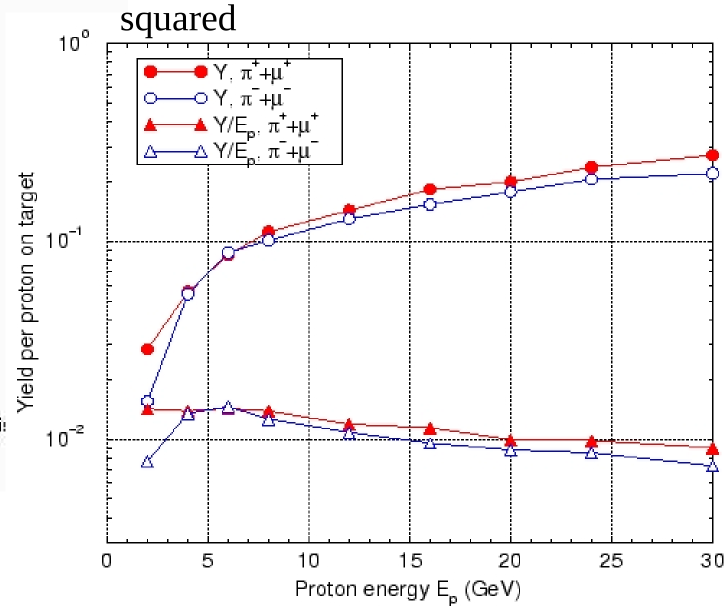


Figure 4.12: Average power dissipation in different 1 cm radius targets due to 8 GeV i
beam of 6×10^{13} protons at 30 Hz. Beam rms spot size $\sigma_x = \sigma_y = 4$ mm.

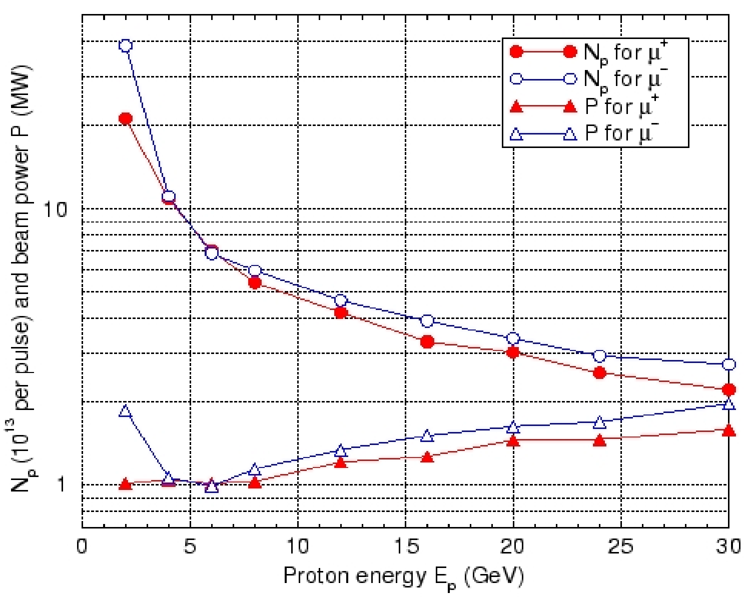
Pion production on Carbon

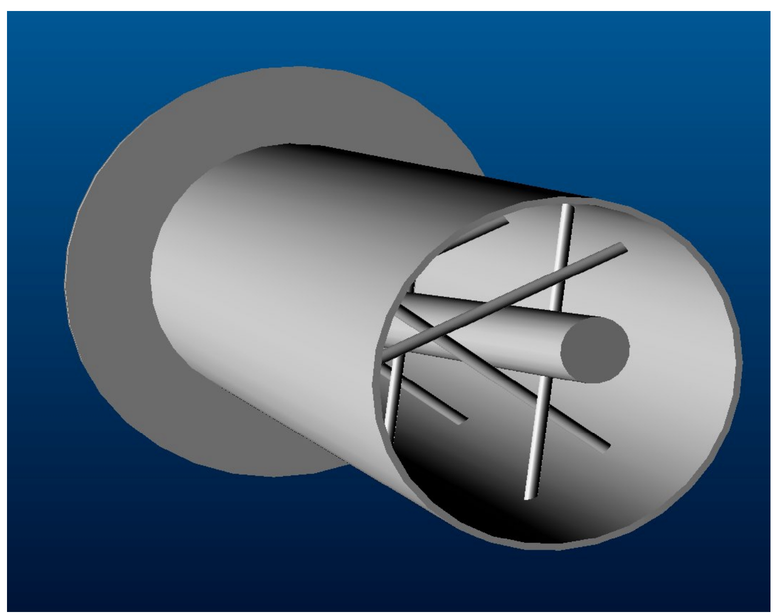
- Neutrino Source: Physics ∝ number of muons produced.
- MC: Physics ∝ number of muons squared



Beam power required?

- Minimum at 5-6 GeV for Carbon target





Radiation at the Target

Iron shielding

Air

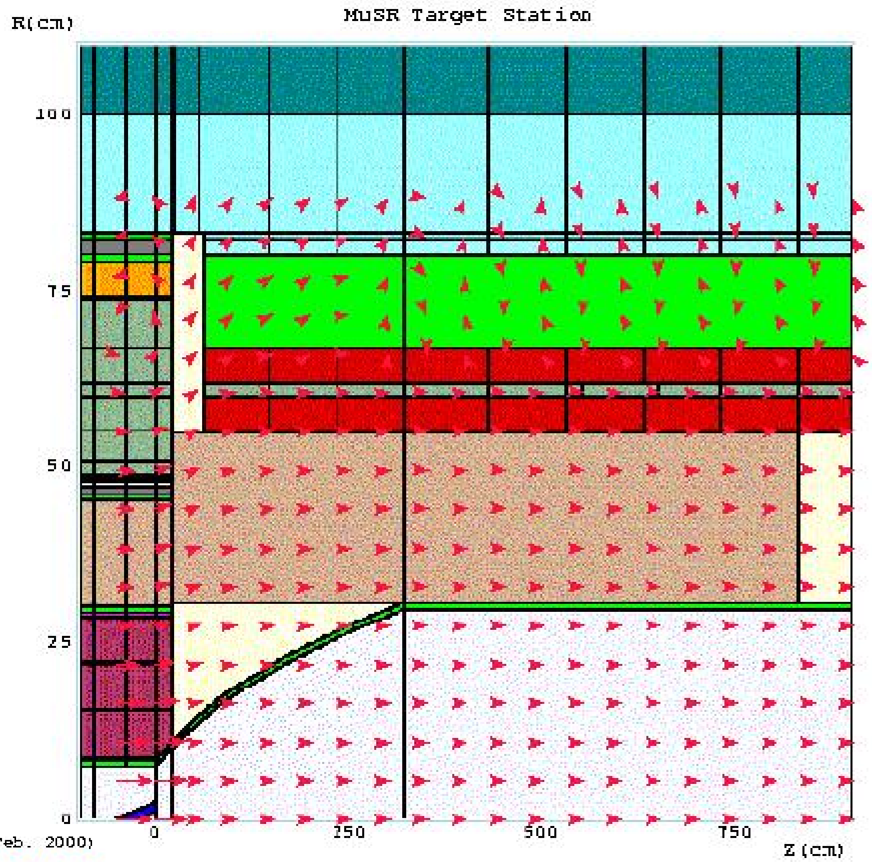
Cryostat

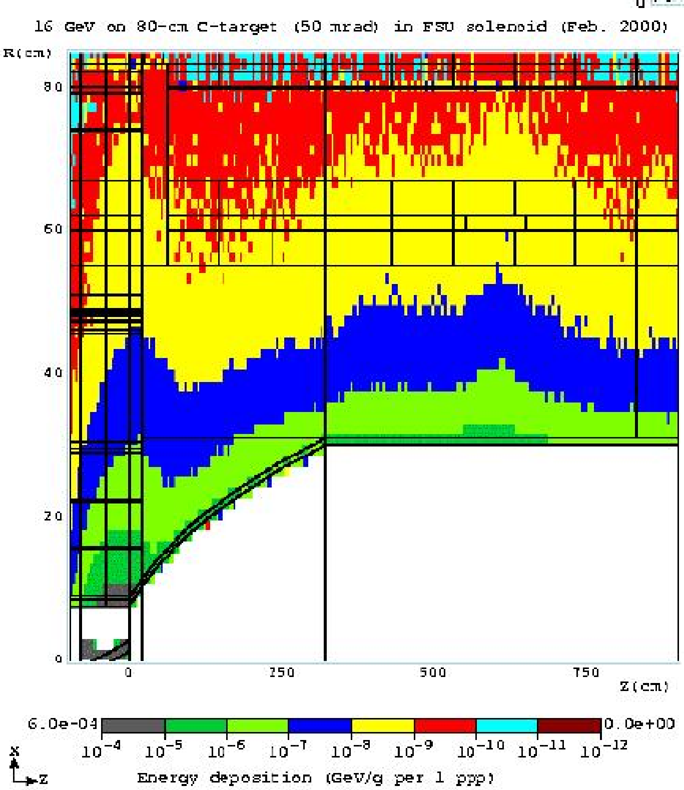
sc coil

tungsten-carbide
+water

nc coil (=10 MW)

rod tilted, 50 mrad





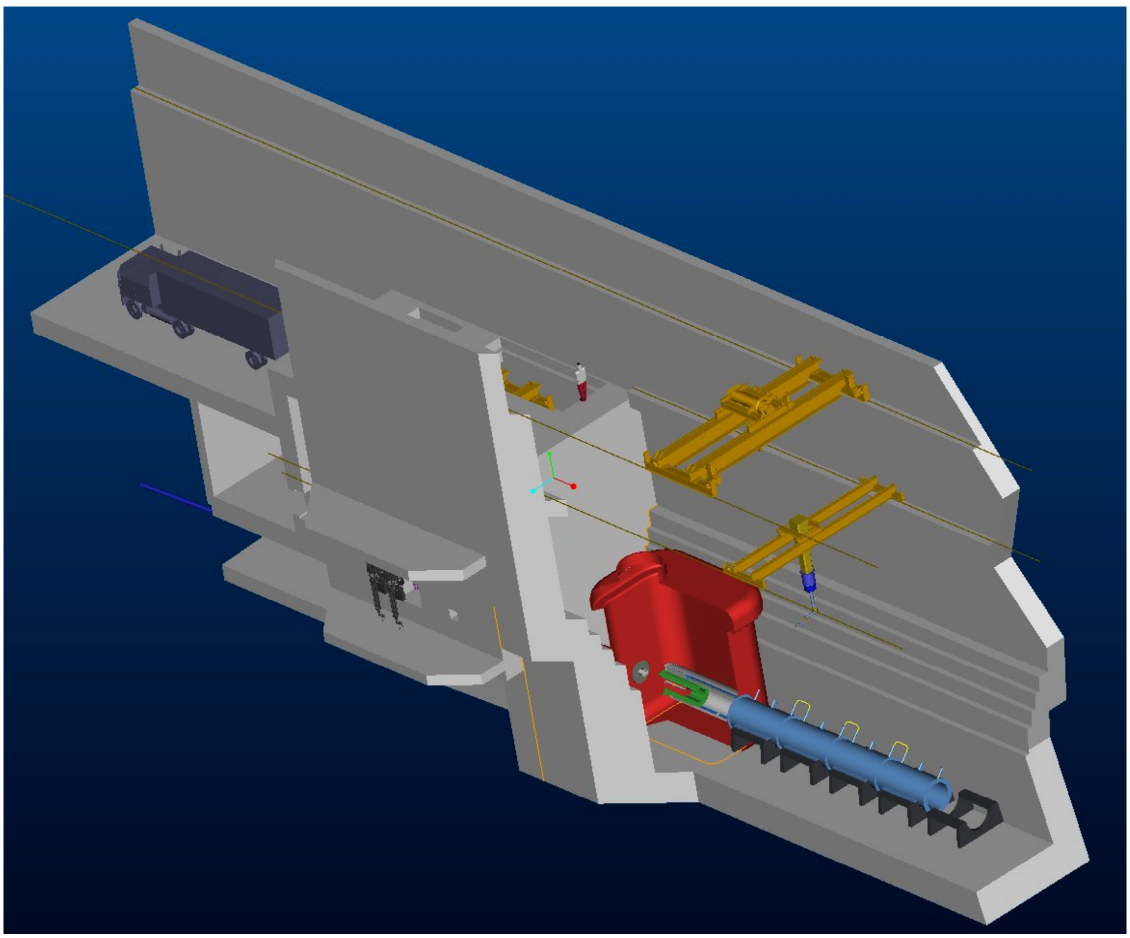
- Flux: few x 10^{10} Gy (0.01 Gy=1rd)
- very hot area

Target for a Neutrino Factory

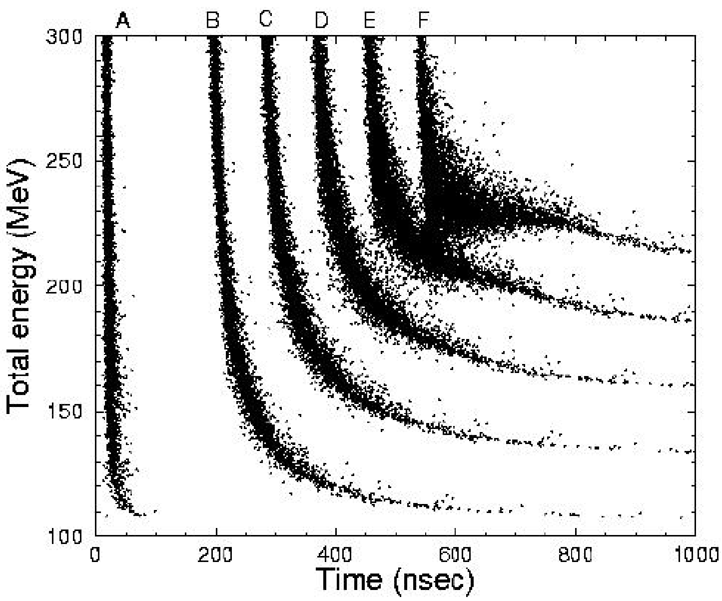
- 1.5 - 4 MW target station and infrastructure for it
- designed a 1.5 MW target
- Reduce power in the target → low Z → compromise yield
- Lifetime: limited by cavitation in nc Coil: 10 MW dissip. Power

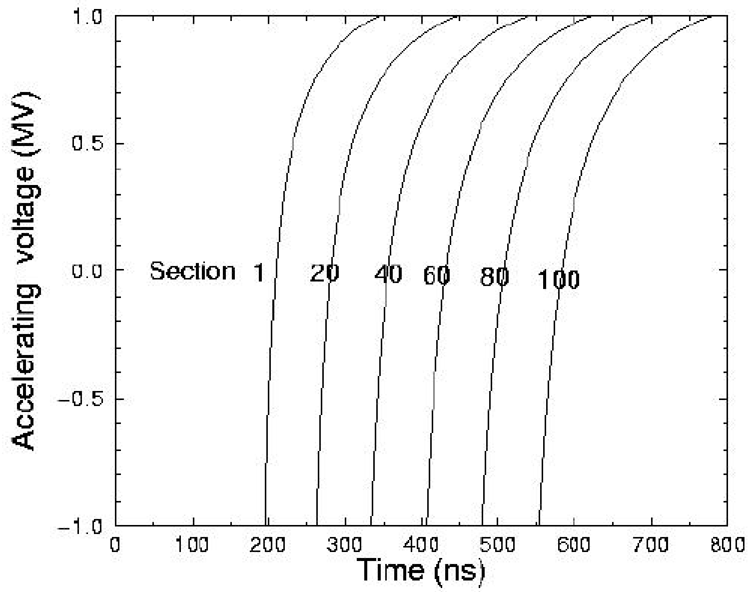
- Very intense radiation in the target area
- Beam dump is integrated in Magnet shielding
- Target lifetime due to radiation ~ 3 month→ 80 cm 2cm rad carbon rod

- Target hall designed by Oak Ridge.
- 1.5 - 4MW Target infrastruct.
- Radiation cooled strained fiber carbon target (2400 C°)



Decay Channel, Induction Linacs, and Rebunching





50 m drift before φ rotation

<u>For carbon target</u>:

0.10 μ/p between 225 - 240 MeV

0.13 μ/p between 220 - 250 MeV

0.18 μ/p between 200 - 270 MeV

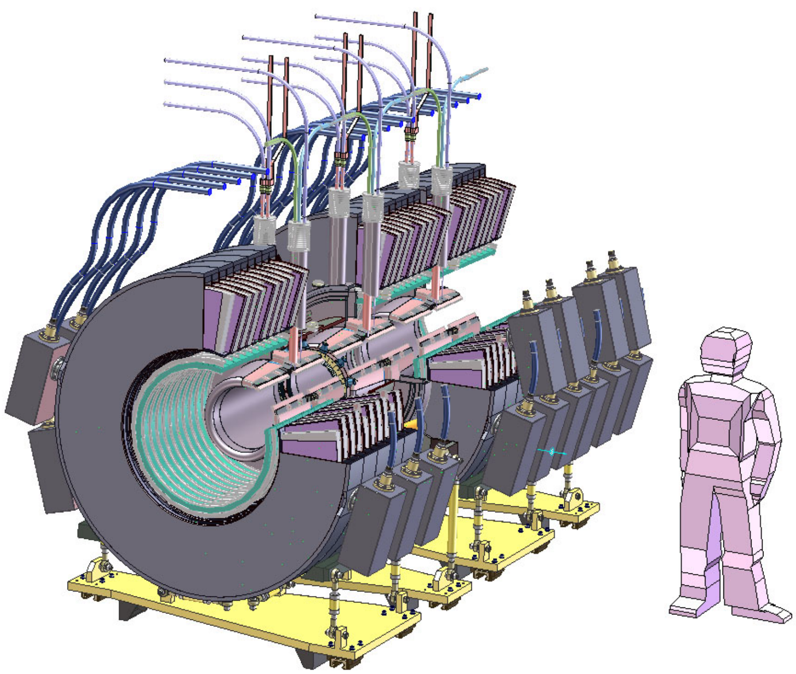
Trade off:

Energy Spread after rotation⇔ drift channel length [loss]

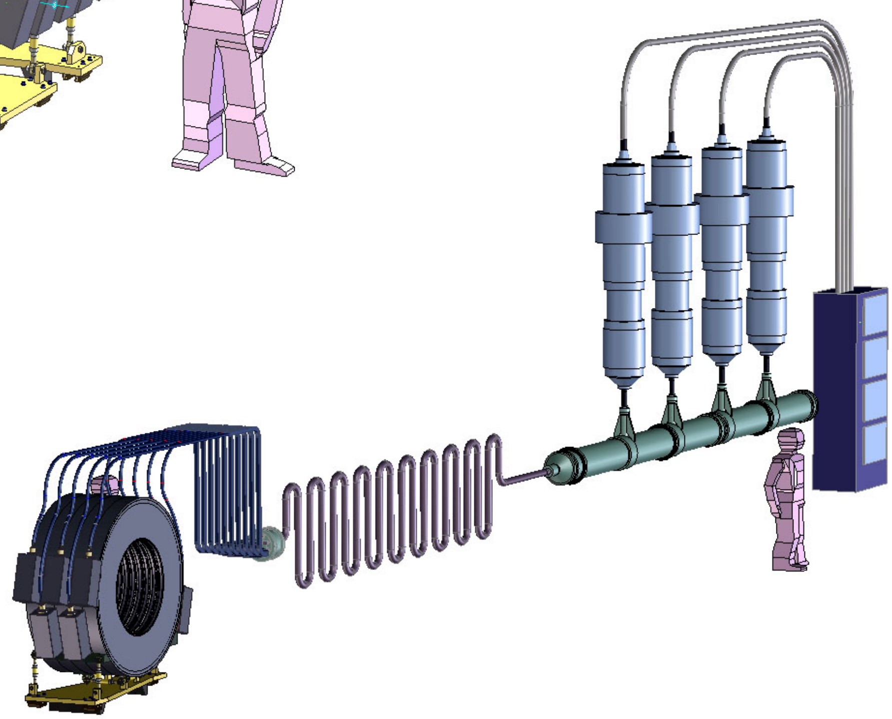
Particle capture⇔length(voltage) in induction linac [loss]

Induction Linac Layout

- Strong Effort at LBL for DAHRT+ imported Expertise at Fermi: 4 pulses per cycle in 2 μsec (booster circ.)
- higher field 2-3 T and smaller cores may be better solution
  - saturation in the cores is under control
  - switching is the main problem
  - sc coil inside of an induction linac



Switching of voltage ?

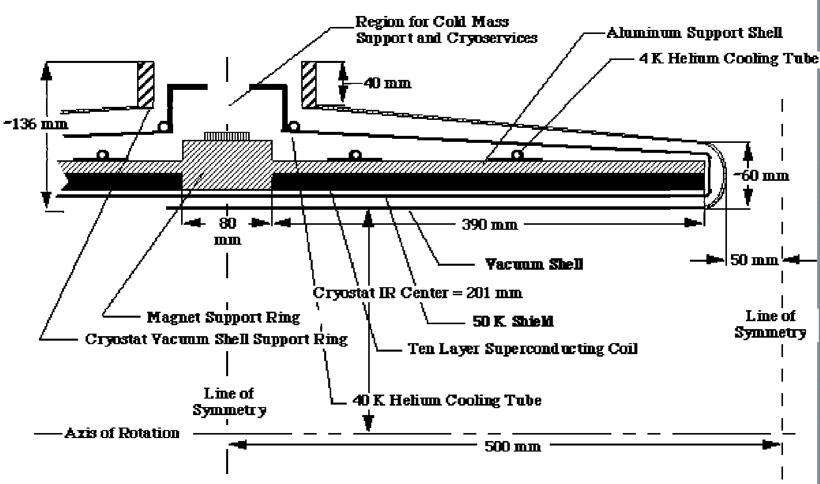


Induction Linac Construction

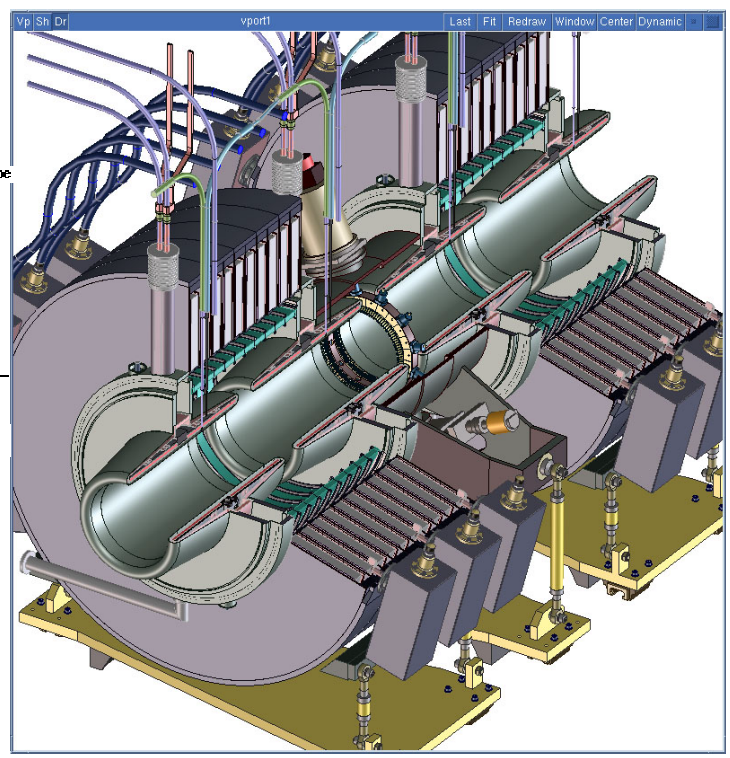
- Induction cell with 1.5-3.0 Tesla coil inside
  - high gradient -- 4 pulses -- sc solenoid inside
  - Power consumption: 4 pulses 15 Hz$\rightarrow$8 MW

ΔV	V_{eff}	τ_r	τ_{flat}	τ_{eff}	$v\tau$	Type	δ	PF_r	ΔB_{max}	Cost	
kV	kV	μs	μs	μs	mV-s		gm/cc		T	Norm	
200	**142**	0.070	0.030	**0.07**	**12.6**	**Finemet**	7.32	0.70	**1.95**	**1.00**	**<-- Finemet**
200	**142**	0.070	0.030	**0.07**	**12.6**	**2605SC**	7.32	0.70	**2.90**	**0.36**	**<-- 2605SC**
200	**142**	0.070	0.030	**0.07**	**12.6**	**2605SC**	7.32	0.70	**1.10**	**2.00**	**<-- 2714A**

ΔB	A_{Met}	A_{Core}	$\Delta B/\Delta t$	L		Δr	r_i	r_o	r_o / r_i	r_{Mean}	H	I_{Core}	E_{core}	k	U_{Met}	V_{Met}	W_{Met}	System $
T	cm^2	cm^2	T/μs	"	cm	cm	cm	cm	cm	cm	kA/m	kA	J	J-μs/T-m³	J/m^3	cm^3	kgm	Norm
0.97	130	185	**13.2**	2.28	5.8	32.0	45	**77**	1.71	61.0	0.65	**2.50**	31.5	**107**	**634**	49670	363.6	**1.00**
0.82	154	220	11.1	2.28	5.8	37.9	45	**83**	1.84	64.0	0.55	**2.23**	28.1	107	454	61744	452.0	1.02
1.48	85	122	20.1	2.28	5.8	21.0	45	66	1.47	55.5	0.98	3.41	42.9	107	1445	29688	217.3	1.07
0.82	154	220	**11.1**	2.28	5.8	38.0	45	**83**	1.84	64.0	0.98	**3.94**	49.6	**282**	**801**	61946	453.4	**1.13**
2.20	57	82	29.8	2.28	5.8	14.1	45	59	1.31	52.1	2.53	8.28	104.4	282	5571	18736	137.1	2.07
0.82	154	220	**11.1**	2.28	5.8	38.0	45	**83**	1.84	64.0	0.37	**1.50**	18.9	**41**	**306**	61946	453.4	**1.35**
0.86	147	209	11.7	2.28	5.8	36.1	46	82	1.79	64.1	0.39	1.59	20.0	41	339	58981	431.7	1.33

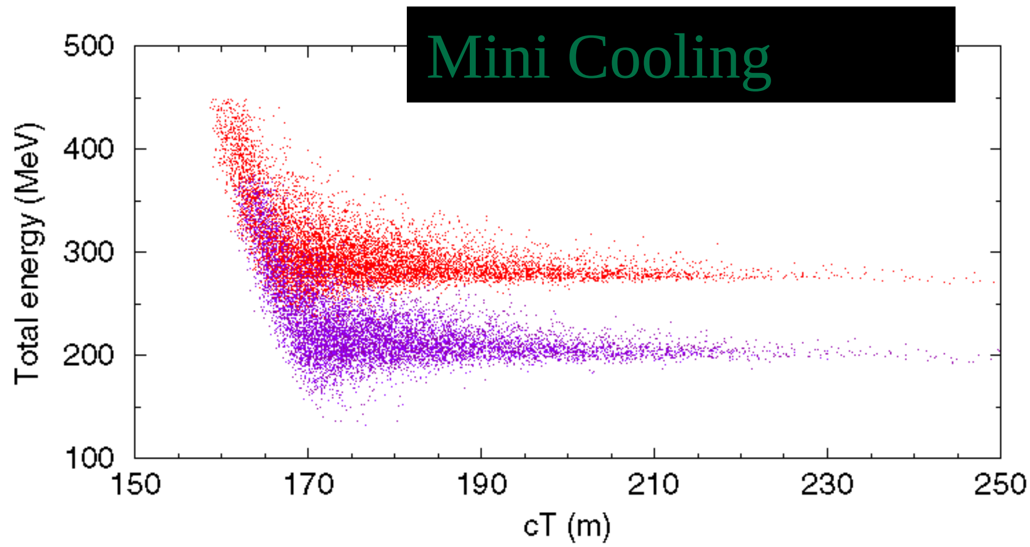


Quarter Section of a 3.0 T Solenoid for the Phase Rotation System

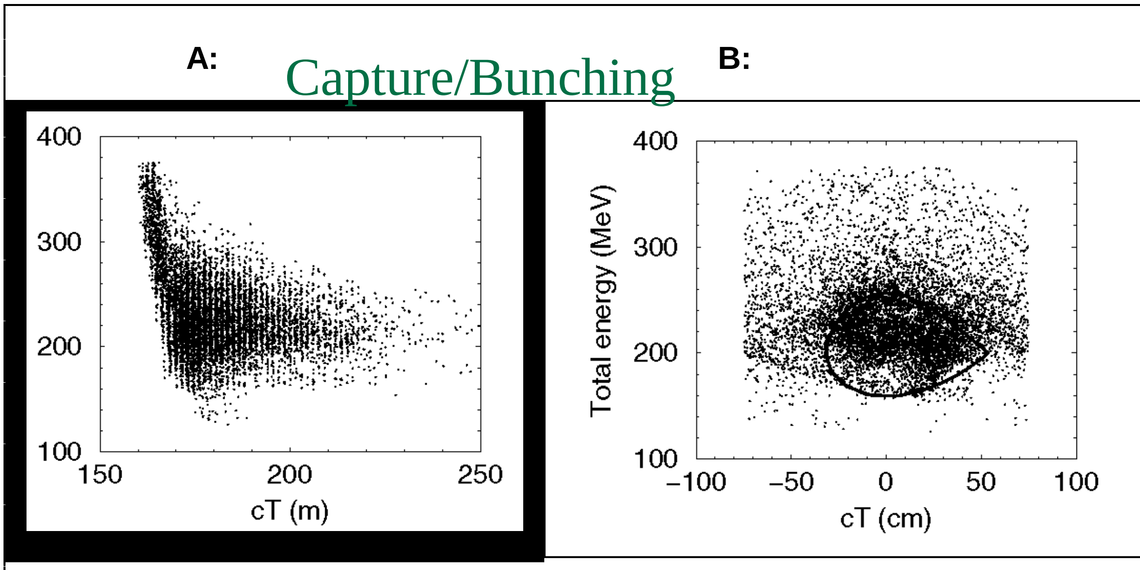


Bunching and Capture

- $\Delta E/E$ after phase rotation
- bunching into string of 35 bunches or so



Longitudinal phase space distributions of the μ=beam before (above, red) and after (below, violet) the minicool energy loss insert.

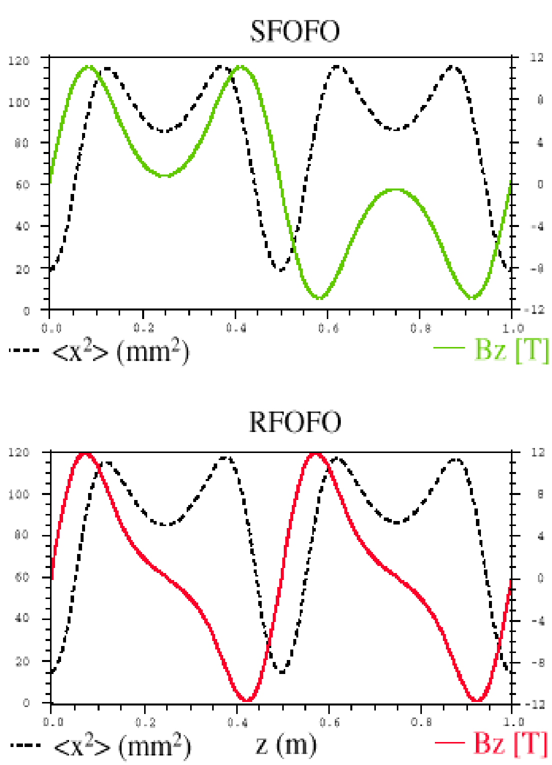


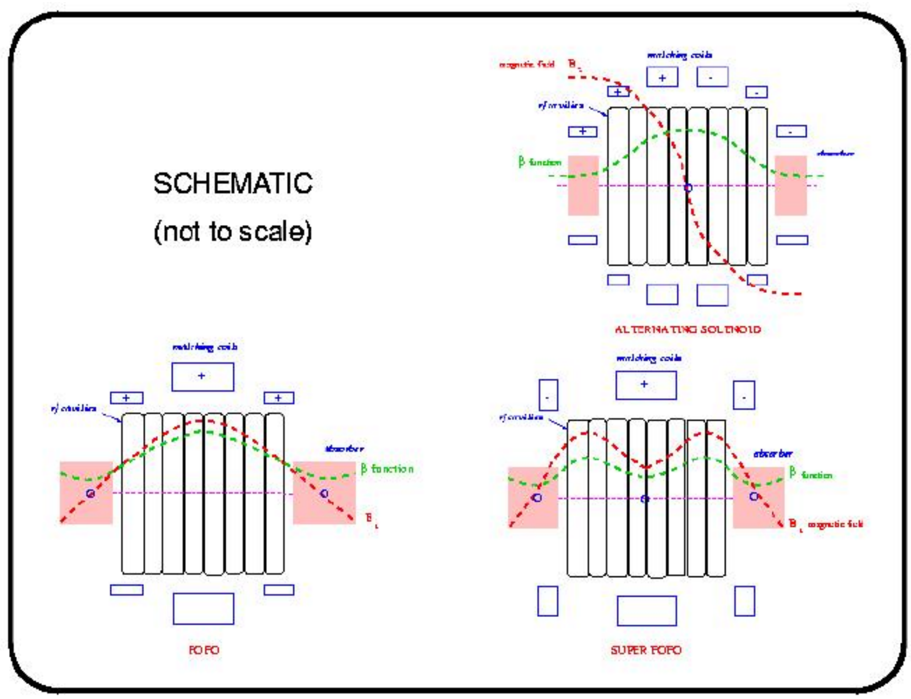
Beam distributions in energy –distance coordinates. A shows the full beam length; B shows the distribution folded over the 201.25 MHz periodicity, with an RF bucket for 200 MeV, 200 MHz cooling.

Simulation Effort at LBNL

- "From the Target through the Cooling"
  - Different Lattice types
  - Cell length ~ Coil diameter $\Rightarrow$ non efficient use of H_{crit}
  - Field 3.5-7 T or more $\Rightarrow$ Ni_3Sn with this kind of diameter
  - <u>Analytical description $\Rightarrow$ G. Penn, LBL / K. Kim ANL+Univ. Chicago/ Y. Derbenev, Michigan State/FERMI</u>
  - Joint effort between FNAL -LBL- BNL to design cooling channels

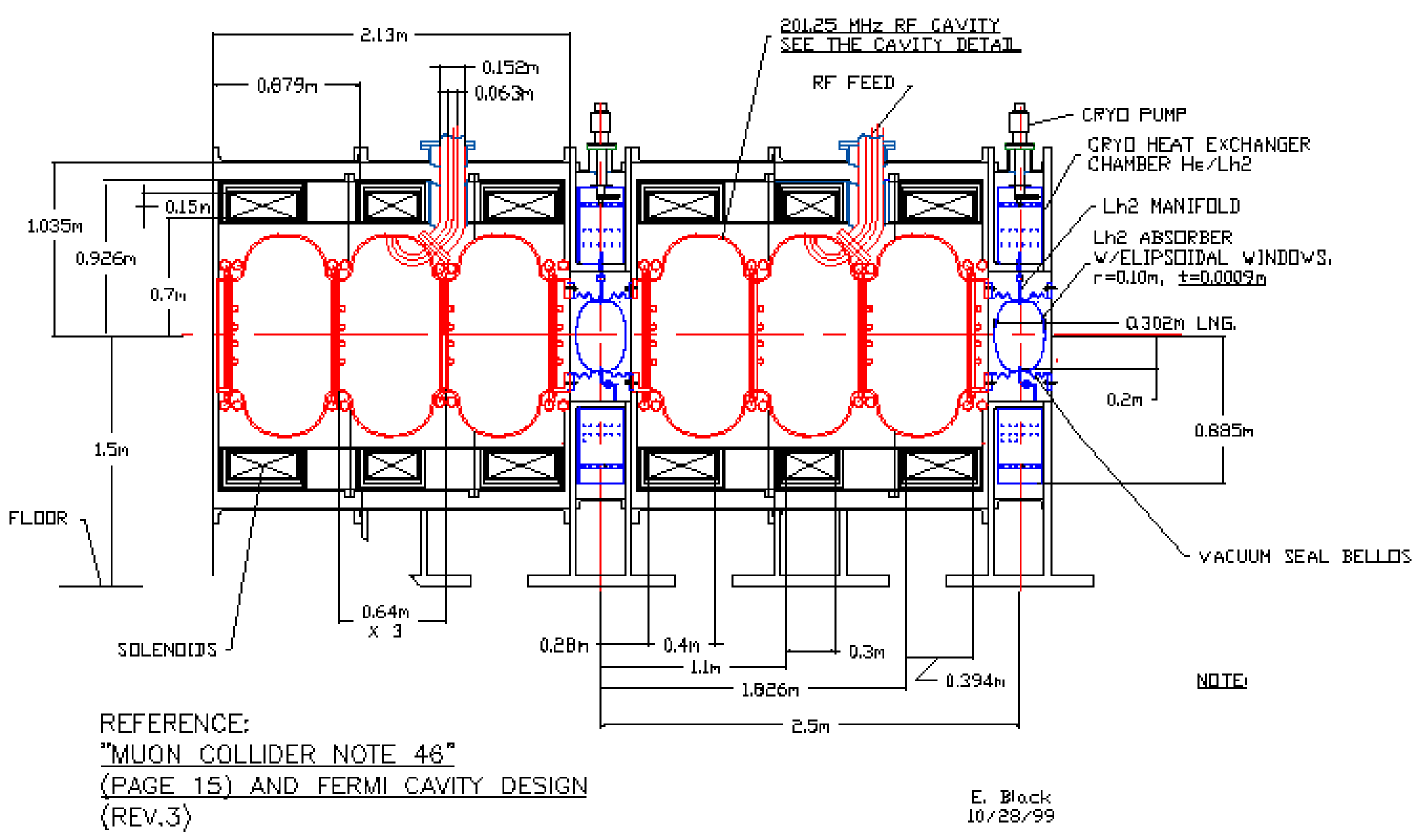
Fields and beta functions: two examples
(note $\langle x^2 \rangle \propto \beta$)





The Heart of the Cooling Channel for a Neutrino Factory

- IIT, BNL, LBNL, FNAL: go through an engineering design faster
  - S. Geer about the MUCOOL program
  - M.Cummings about LH2 absorber
  - J. Miller ⇒ talk more about the detailed work on solenoids
  - J. Corlett about the rf
  - ??? About the induction linac

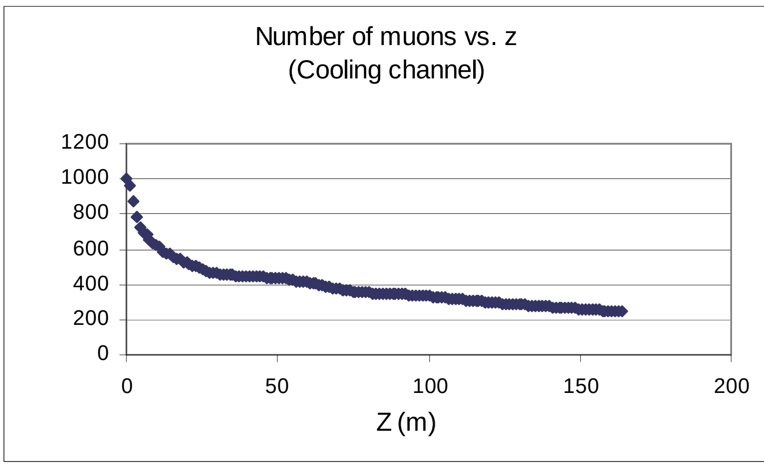


B_z ~ 3.5 T max

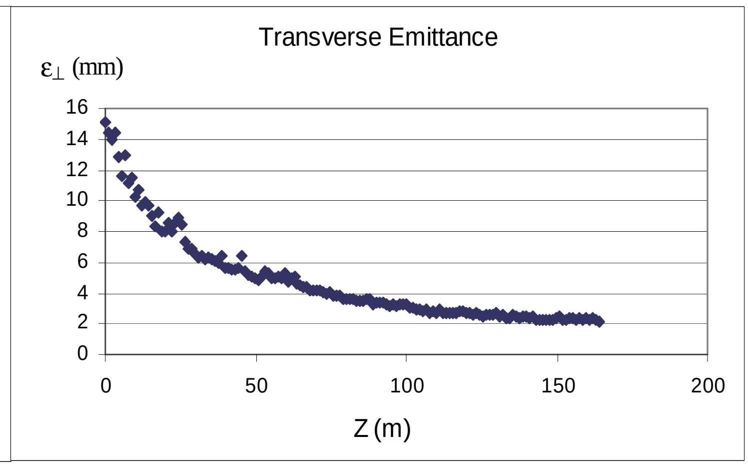
E_{acc} ~ 15 MV/m @ 200 MHz

Ideal Cooling Channel

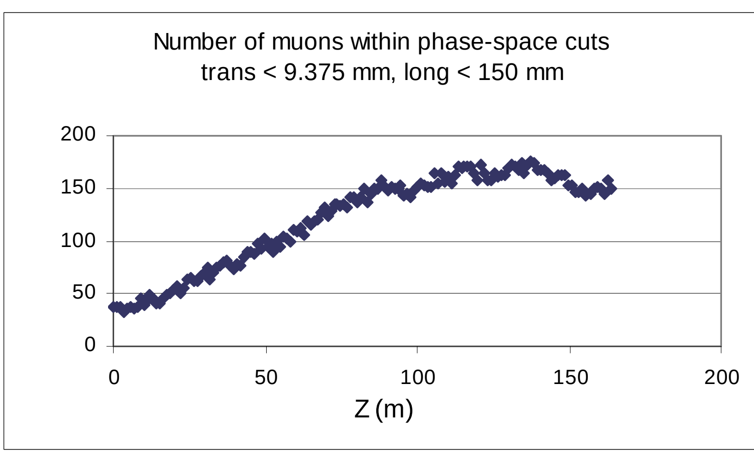
– Small enough $\Delta p/p$ and σ_z
– no correlation between transverse position and longitudinal momentum



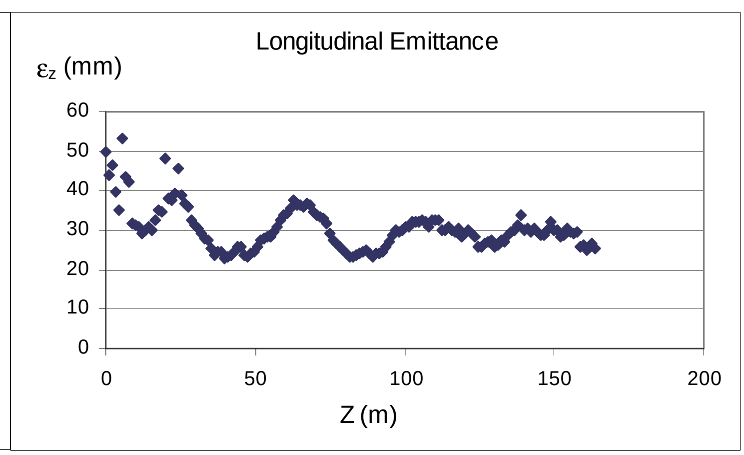
a: Transmission in the FOFO channel vs. distance using the idealized beam described in the text.



b: Transverse emittance vs. distance for the idealized beam.



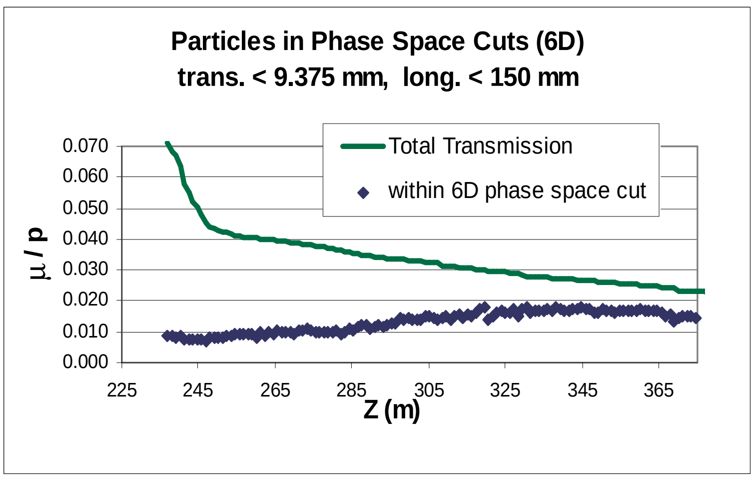
c: Relative yield increase within the acceptance of the accelerator (9.375π mm.rad transverse, 150π mm longitudinal) using the idealized beam.



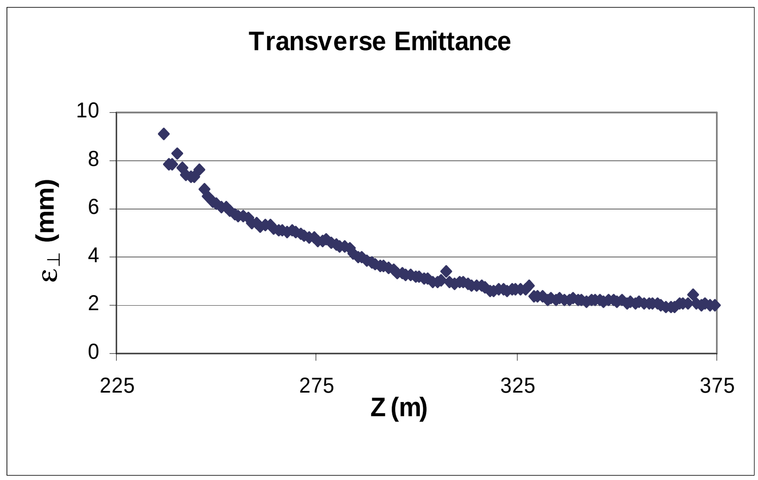
d: The longitudinal emittance of the idealized beam in the FOFO channel

Do We Achieve Our Goal?

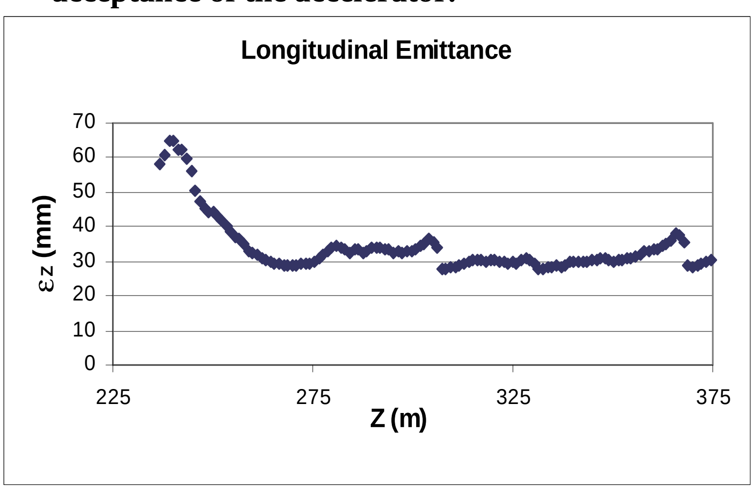
- Nasty question:
  – partially: 5.8×10^{19} shown in the study; no errors included but full simulation.
- Here is were study II will start and improve (⇒B. Palmer, S. Ozaki)



The transmission and the muon yield within the acceptance of the accelerator.



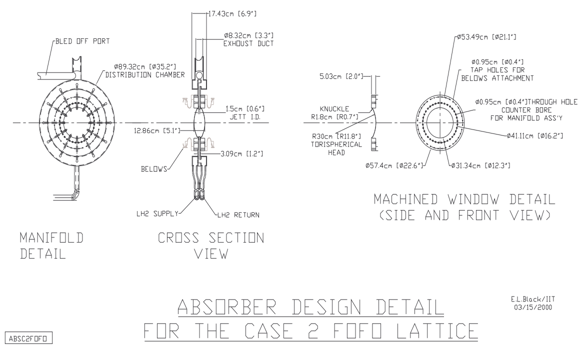
The transverse emittance versus z in the FoFo cooling channel.

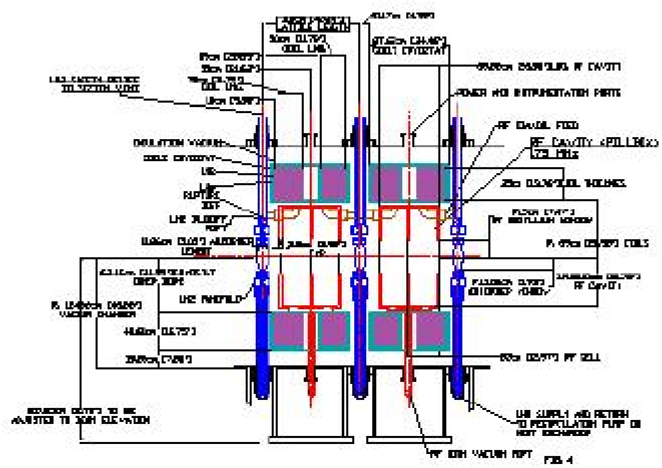


The longitudinal emittance.

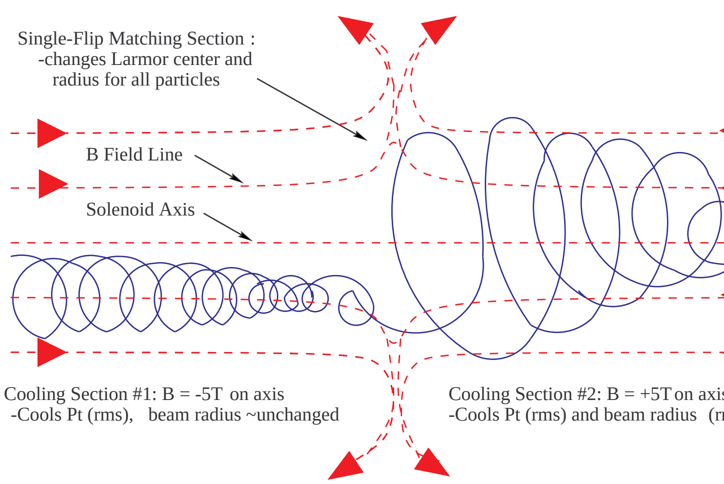
Other Cooling Channels

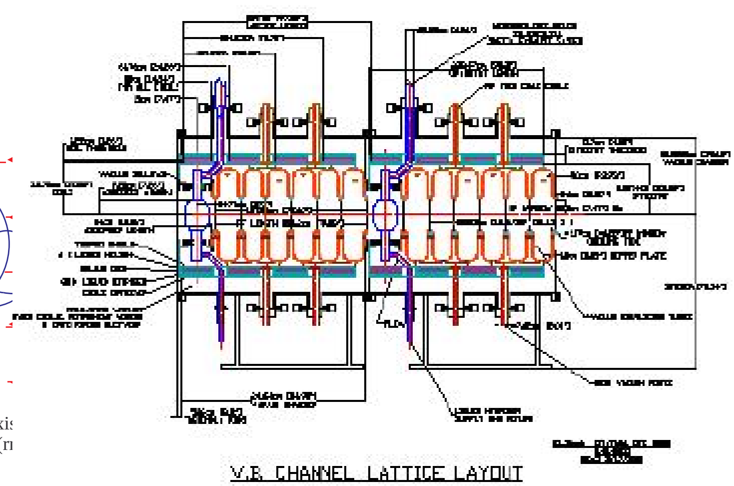
•Baseline: FOFO





• Single Flip

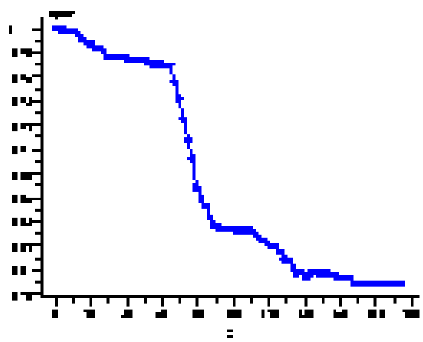




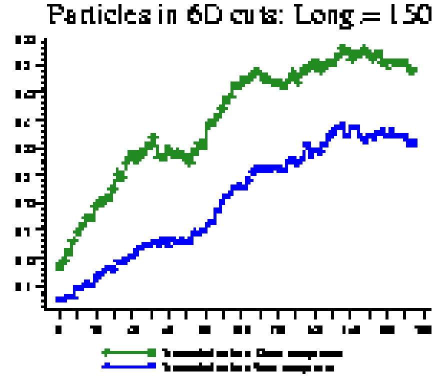
Cooling Simulation & Improvement

- J. Monroe: Single Flip increased performance:
  - Ideal = Matched Longitudinal Phase Space
  - assume 0.22 μ/p into Cooling

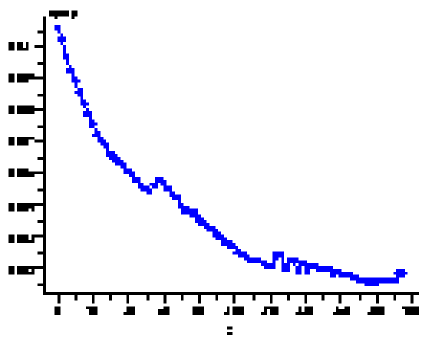
Transmission (%)



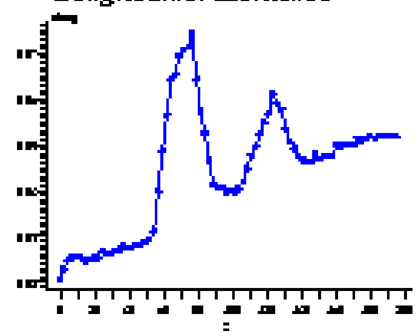
Particles in 6D cuts: Long = 150 mm



Transverse Emittance



Longitudinal Emittance

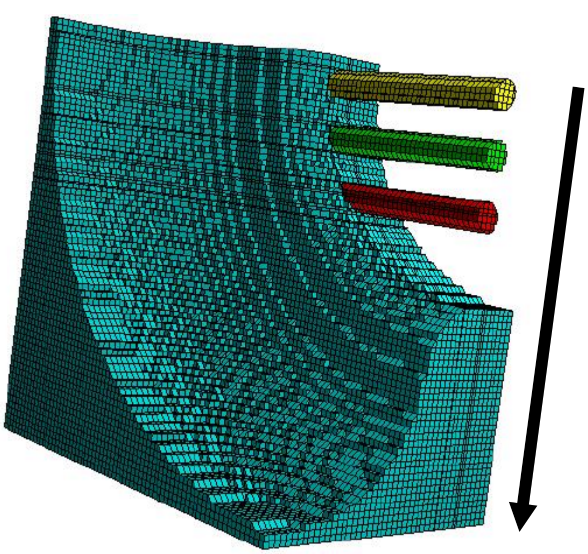


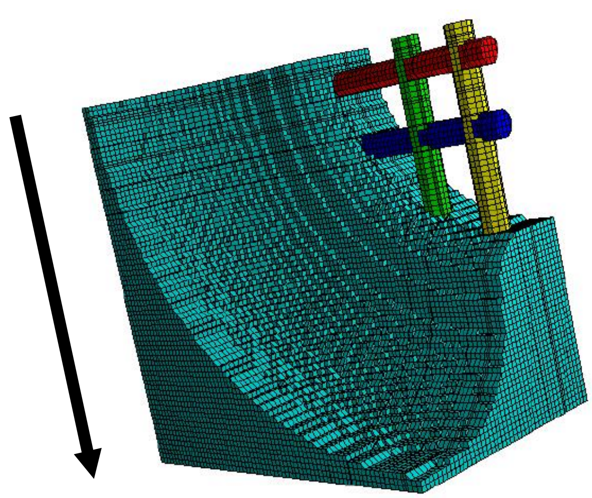
parameter	z = 0 m.	z = 100 m.	z = 150 m.
ϵ_T mm. - Rad.	11.5	3.7	2.9
ϵ_L mm.	20	40	47
N_{9mm} %	7%	28%	35% (0.077)
N_{15mm} %	13%	46%	50% (0.11)
N_{part} (μ/p) %	100 (0.22)	84 (0.185)	80 (0.176)

Cavity Parameter

J. Corlett

Parameter	Crossed Tube	Pill Box
Frequency	201.25 MHz	201.25 MHz
Accelerat. Phase Angle	Sin(25 degrees)	
Peak Accelerating Field	15.0 MV/m	15 MV/m
Peak Surface Field	22.5 MV/m	15 MV/m
Kilpatrick Limit	14.8 MV/m	14.8 MV/m
Cavity Type	crossed tubes	Beryllium foil windows
Shunt Impedance	20.3 M? /m	23.3
Transit Time Factor T	0.845	0.827
Peak Voltage per Cell	6.5 MV	5.7 MV
Q	47,500	52,600
Fill Time	38 µs, critic. coupled	42 µs
rf Pulse	114 µs	125 µs
Peak Power per Cell	3.45 MW	2.8 MW
Average Power per Cell	8.0 kW	5.3 kW
Window Type	4 cm diameter Al crossed tubes	15 cm radius, 127 µm thick Be foil
Average Power on Tubes	30 W (worst tube)	53 W (heated from both sides)

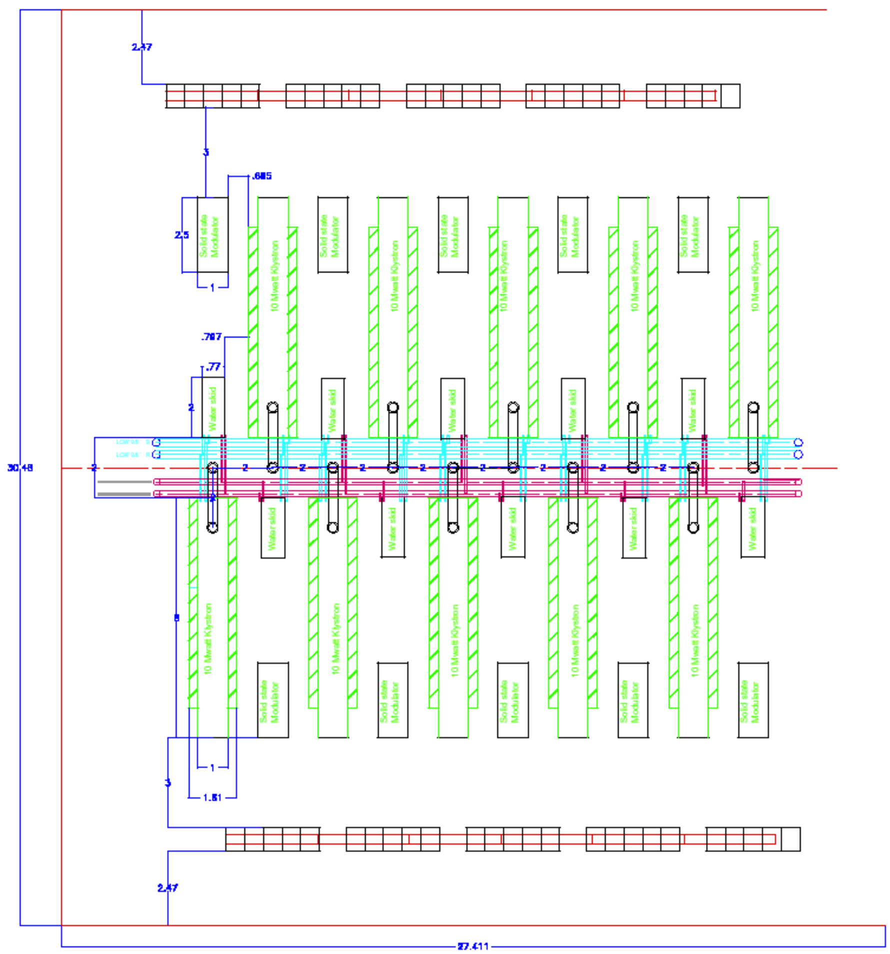




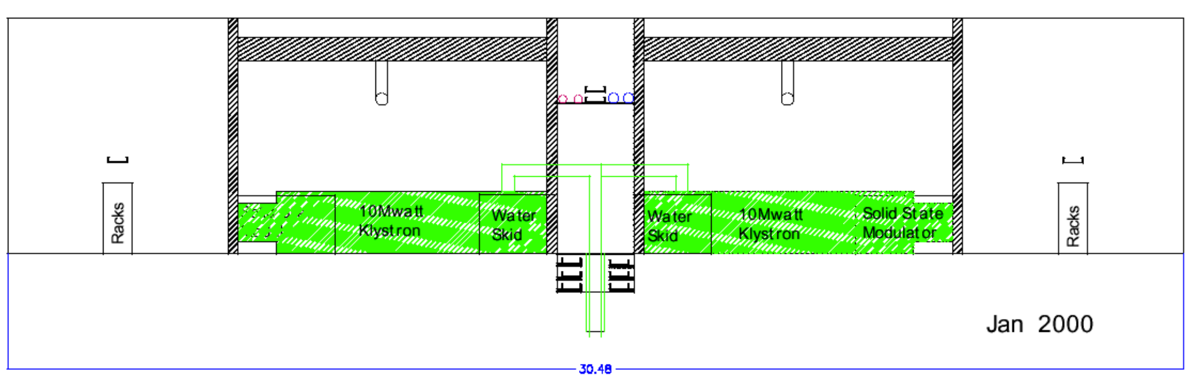
The Cooling Linac

- 100-150 m of 200 MHz High Gradient RF

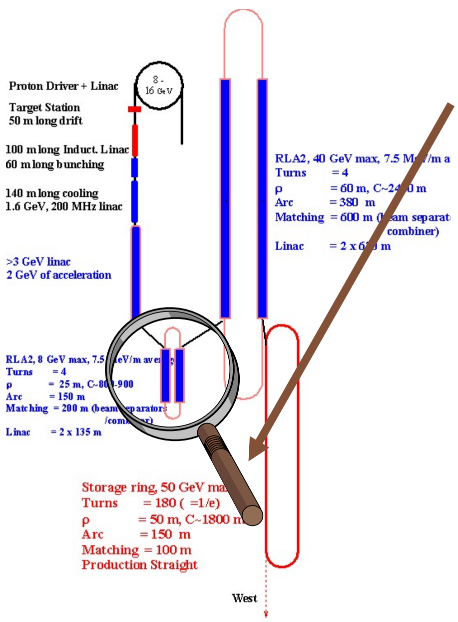
Cooling Channel Linac Equipment Gallery Layout Jan 2000



Cross Section - Cooling Channel Linac Equipment Gallery



Basic Result from Accel. Meeting



- V. Lebedev ⇒
- Acceleration Scenario (TJNAF):
  - 3 GeV linac, sc solenoids, 200 MHz; RLA 1 from 3-11 GeV, at 200 MHz, nc arcs, 4 turns
  - RLA 2 11-50 GeV,400 GHz, 5 turns, sc arcs
  - cost model available which everybody agreed on
  - 41 x 200 MHz klystrons with Tp=2 msec and 15 Hz are required + 70 Modulator for the whole acceleration
  - issue:ΔF≈80 Hz per cavity which is given loaded Q: ~ $3x10^6$

•Cavity R&D (Cornell Univ.,NSF ⇒Tigner, Padamsee):

•build 200 MHz model and measure microphonics

•coupler development is relaxed (800 kW (200 MHz) 200 kW (400 MHz))

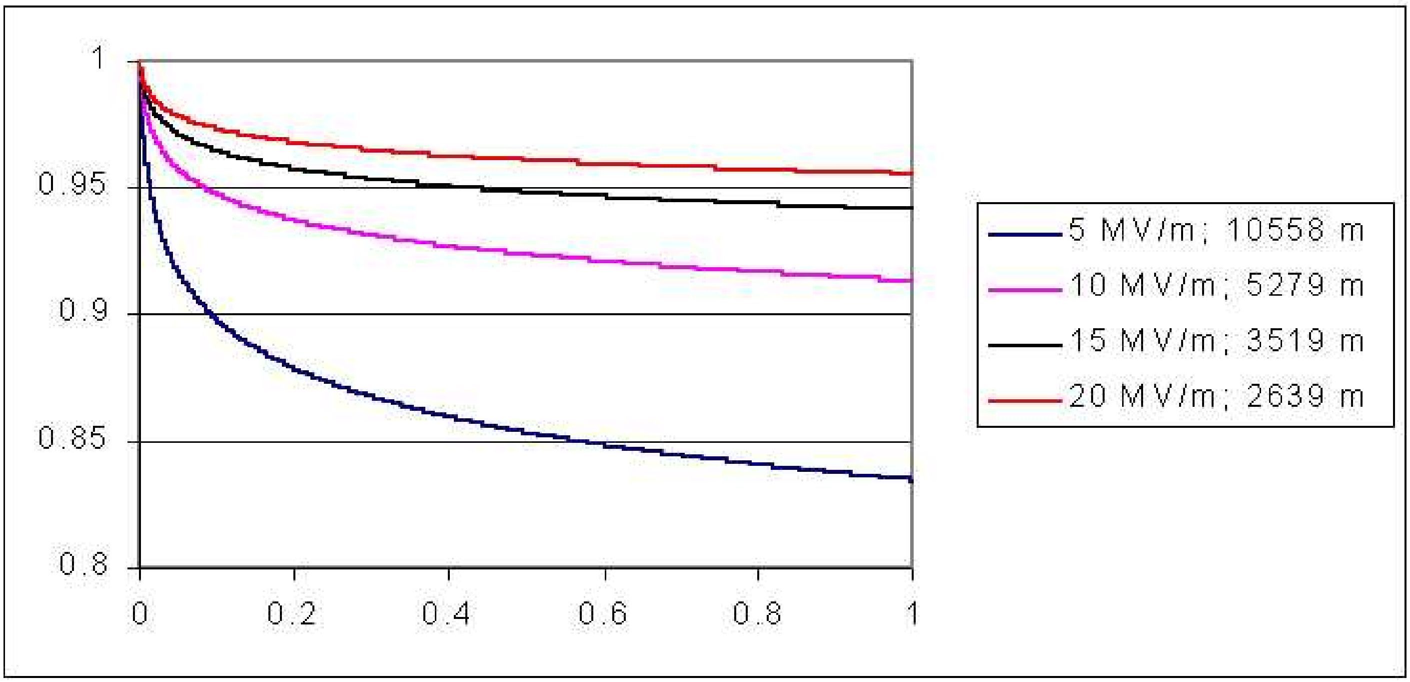
•Klystron (SLAC ?):

•~ 70 Klystron or so are needed for the whole scrf acceleration

•big R&D plan: 10 MW @ 2 msec, 200 MHz+400 MHz.

•Modulator: TESLA type

Acceleration of Muons



- Muon Survival
  - requires high gradient
  - large aperture

Limits for Peak Power and Frequency

- What determines the physical size of a klystron

ideal situation with no space charge:

$$z_{opt} = 1.84 \cdot \frac{u_o(V)}{2\pi \cdot f} \cdot \frac{2}{\alpha \cdot \beta}$$

u_o := velocity of electrons = β*c = $(1-1/\gamma^2)^{0.5}$ *c
α := modulation gap voltage/beam voltage
β:= transit time

f = 200 MHz, U_{gun} = 175kV , uP=1.2 , 15 MW Beam power ->
10 MW rf power,

z_{opt} := 10 meter only for the rf part
+ gun + collector ---> easily a 11-12 meter long klystron with a standard approach.

- scaling shows : $z_{opt} \sim 1/f$ klystron becomes longer
- infrastructure in industry can not mechanically accommodate this easily
- test stands are not available

Klystrons as high peak power sources are only feasible below 200 MHz if multi beam tube is used
SLAC and CPI: preliminary discussion going on

Klystron R & D

- Multi Beam Tubes can be “compact”
- Highly efficient
- Very long lifetime

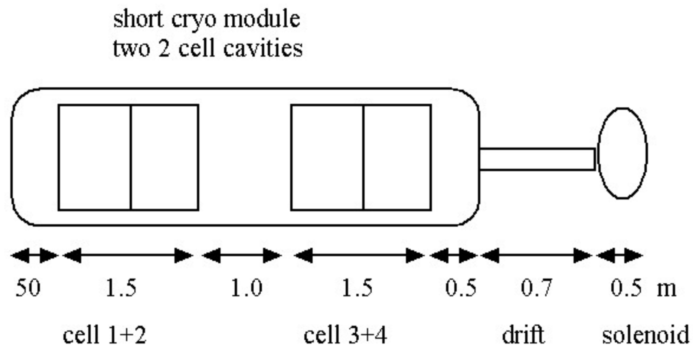
- Alternative: IOT’s, Tubes (see linac)

Frequency, MHz	200			
RF Power, MW	10			
μPerveance , A/V$^{1.5}$	2			
Efficiency, %	44			
Item	Value	Value	Value	Units
Type	ring	3 pole	2 ring+1	-
Number of beams	6	12	19	-
Vb	81	62	51	kV
Itotal	279	368	442	A
Bz	233	251	264	G
Total anode dia	53.3	58.4	60.9	cm
l_q	6.201	5.279	4.759	m
Gun + collector len	1.05	0.87	0.77	m
Total length is from	2.6	2.18	1.96	m
to	4.15	3.51	3.15	m

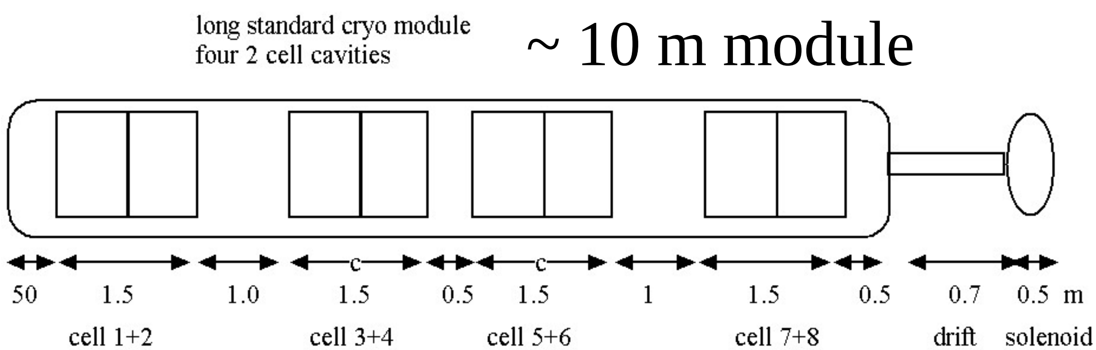
Proposal by SLAC for a klystron design

NSF-Cornell-Jlab-FNAL-TESLA-SLAC

- Super Conducting Cavities and RF Power Sources

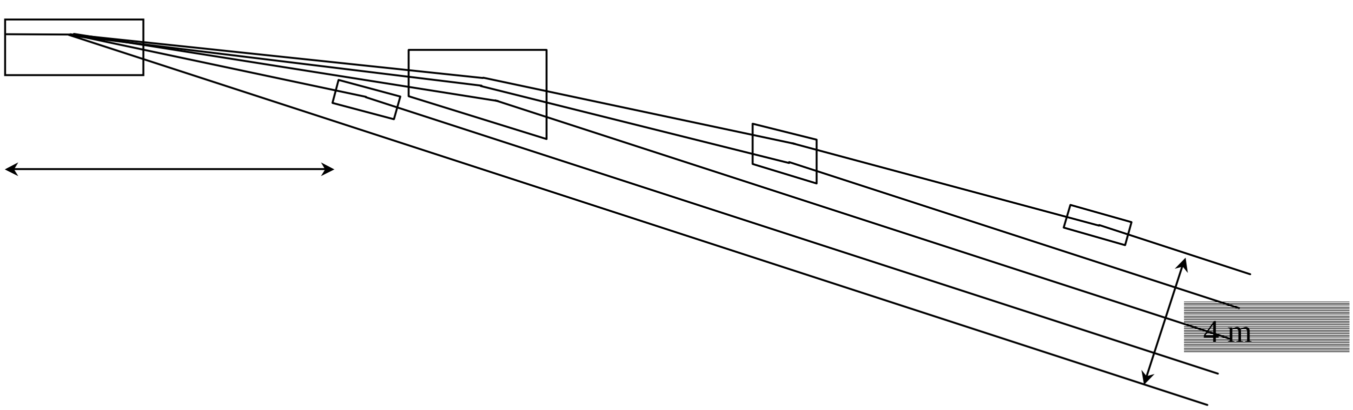


- Acceleration starts 70deg off crest
- 1st part of the linac



- 2nd part of the linac +RLA
- double nr of cells for
- 400 MHz

- Arcs and Beam Spreaders

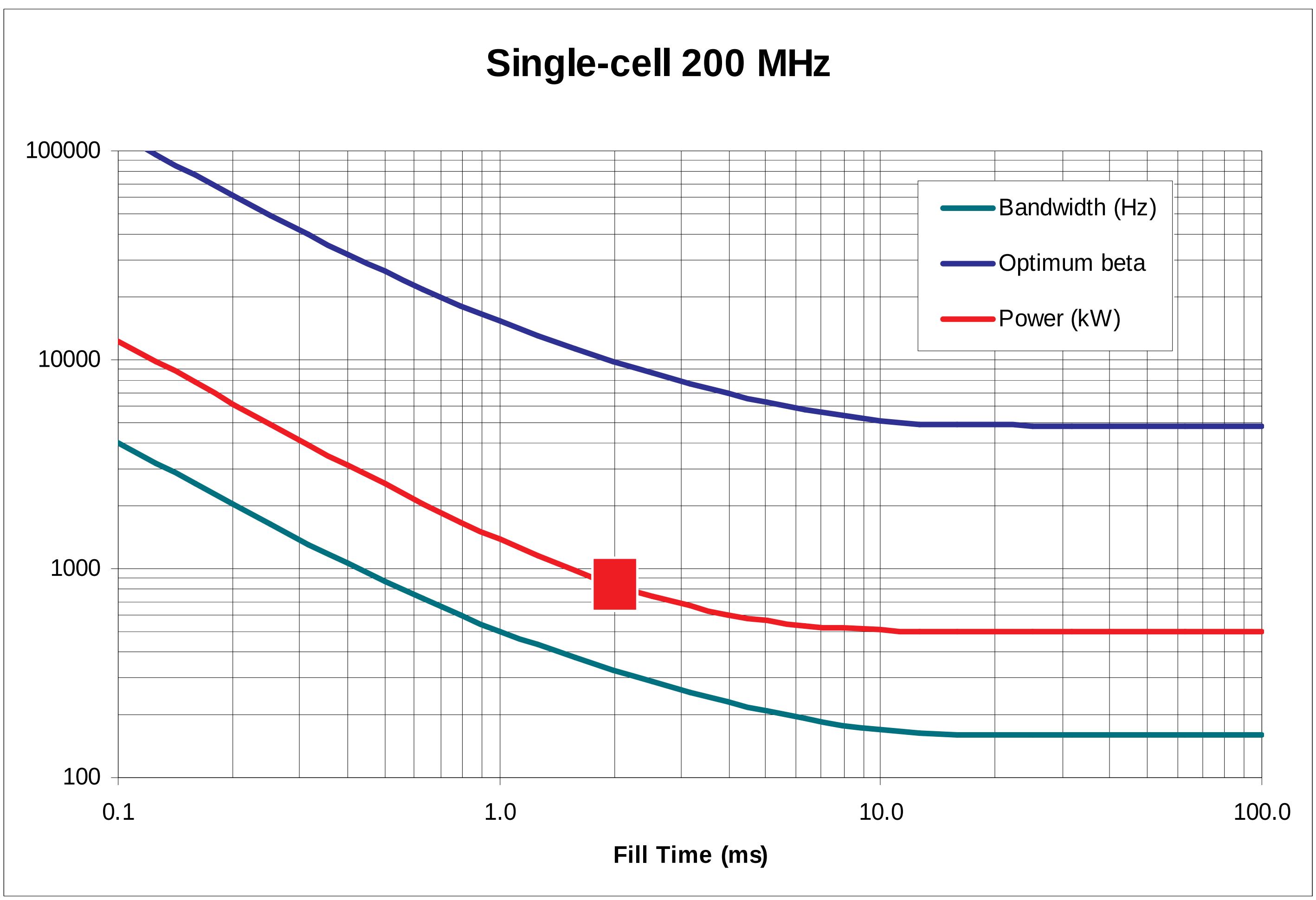


Acceleration with Low Frequency SC Cavities

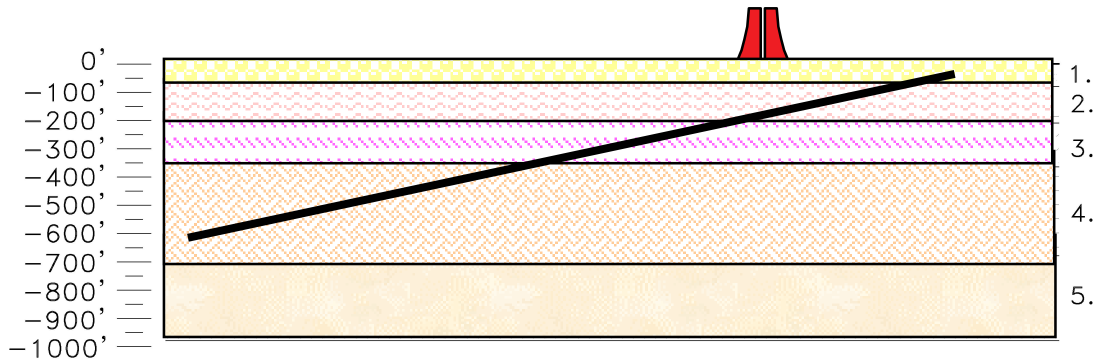
Machine Segment	# passes	$I_{ave.}$ (μA)	V (MV)	$P_{average}$ (W)	U_{stored}/ cell (J)	$P_{control}$ for 80 Hz bandwidth, (kW)
Preaccelerator	1	7.2	11.25	81	1000	503
RLA1	4	28.8	11.25	324	1000	503
RLA2	5	36	5.625	203	125	63

Power extracted per turn: 3.6 J for 200 MHz
1.8 J for 400 MHz

Microphonics + "Lorentz Force Detuning"
especially in large cavities

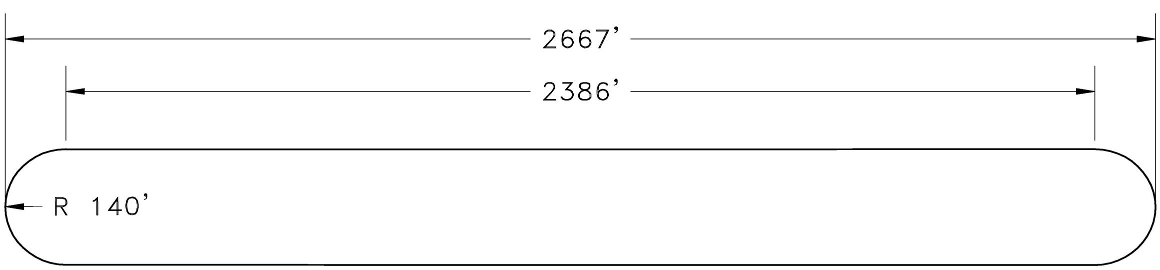


What is Site Specific ?



GEOLOGY DETAIL
1"=100'-0"

1. GLACIAL TILL – AQUIFER
2. SILURIAN GROUP – AQUIFER (PRIMARILY DOLOMITE)
3. MAQUOKETA GROUP – AQUIFER (PRIMARILY SHALE)
4. GALENA / PLATTEVILLE GROUP – AQUATARD (PRIMARILY DOLOMITE)
5. ANCEL GROUP – AQUIFER (PRIMARILY SANDSTONE)



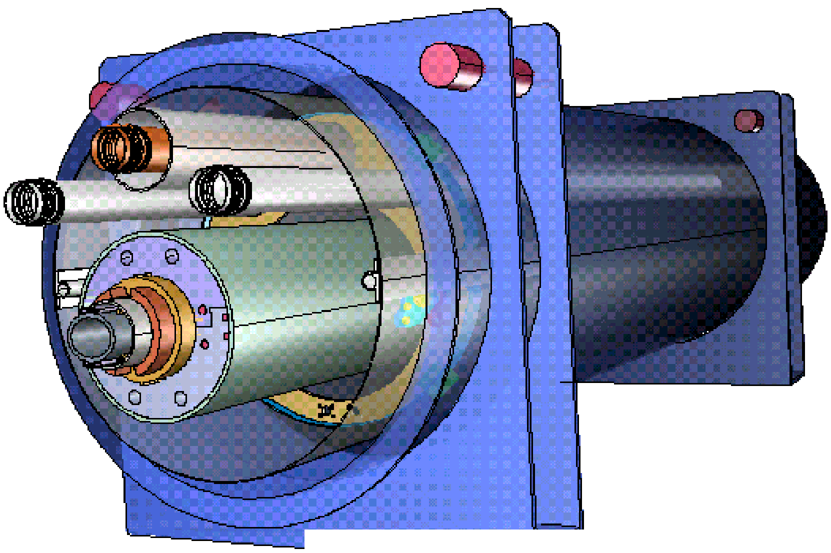
CE 2.1 LATTICE PLAN
N.T.S.

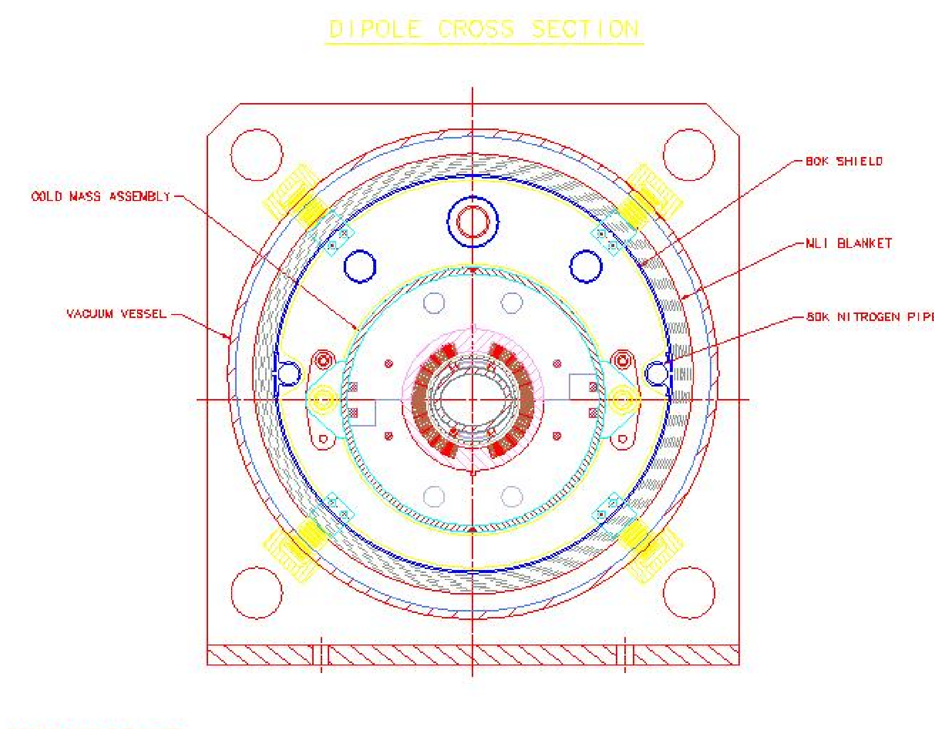
ORIENTATION:

NAME	AZIMUTH (DEG-MIN-SEC)	VERT. ANGLE (DEG-MIN-SEC)
PALO ALTO CA.	271-20'-42.27"	-13-09'-26.99"

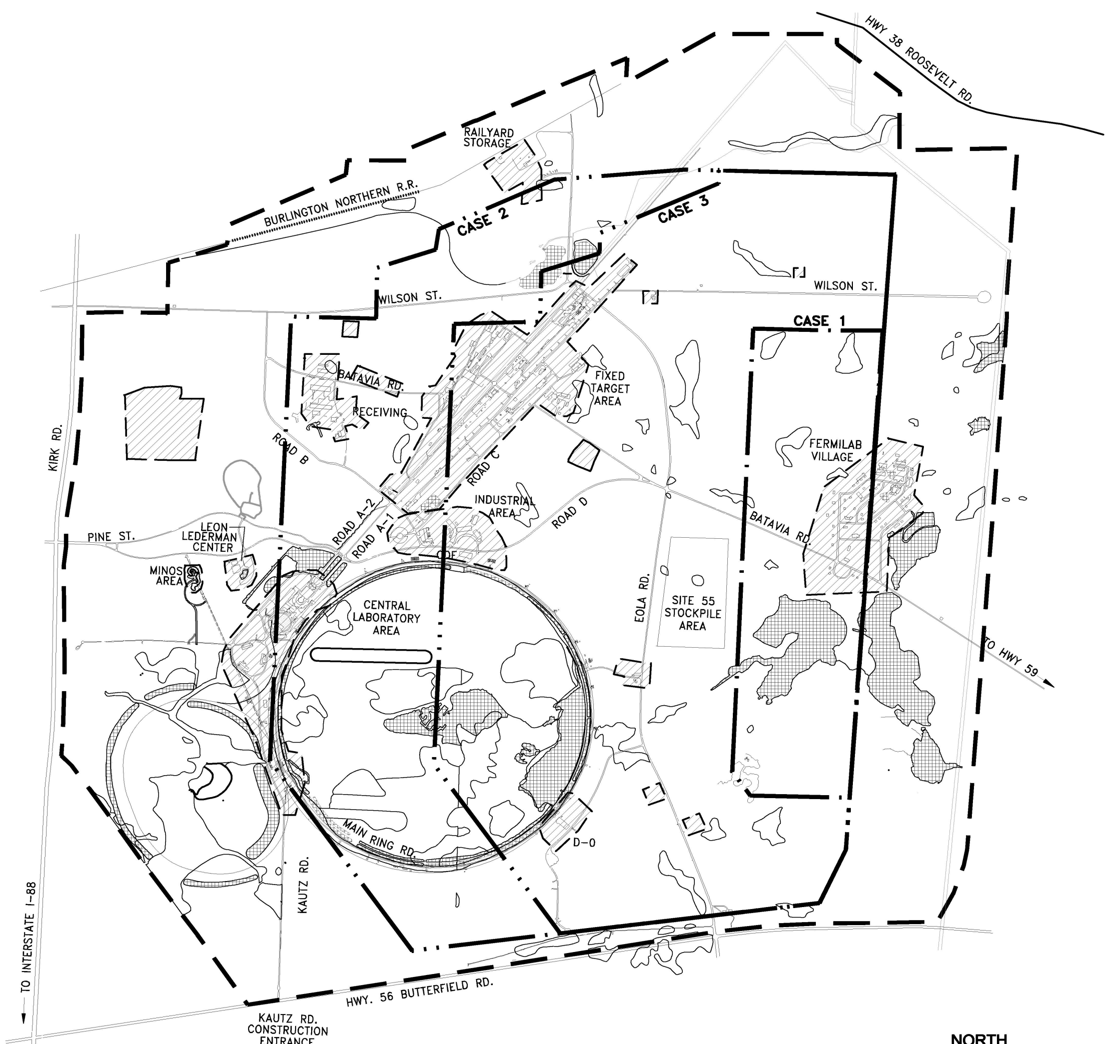
SC Large Bore Magnets

- Low field quality helps reduce price although large aperture
- 7 Watts/m into LHe due to electrons from Muon decay
- 1 cm tungsten (liner instead of 3 cm)





Radiation from the Neutrino Source @ FNAL



LEGEND:

LIMITS CASE 1.
LIMITS CASE 2.
LIMITS CASE 3.
SITE BOUNDARY
LOCATION LIMITS
WETLAND LIMITS

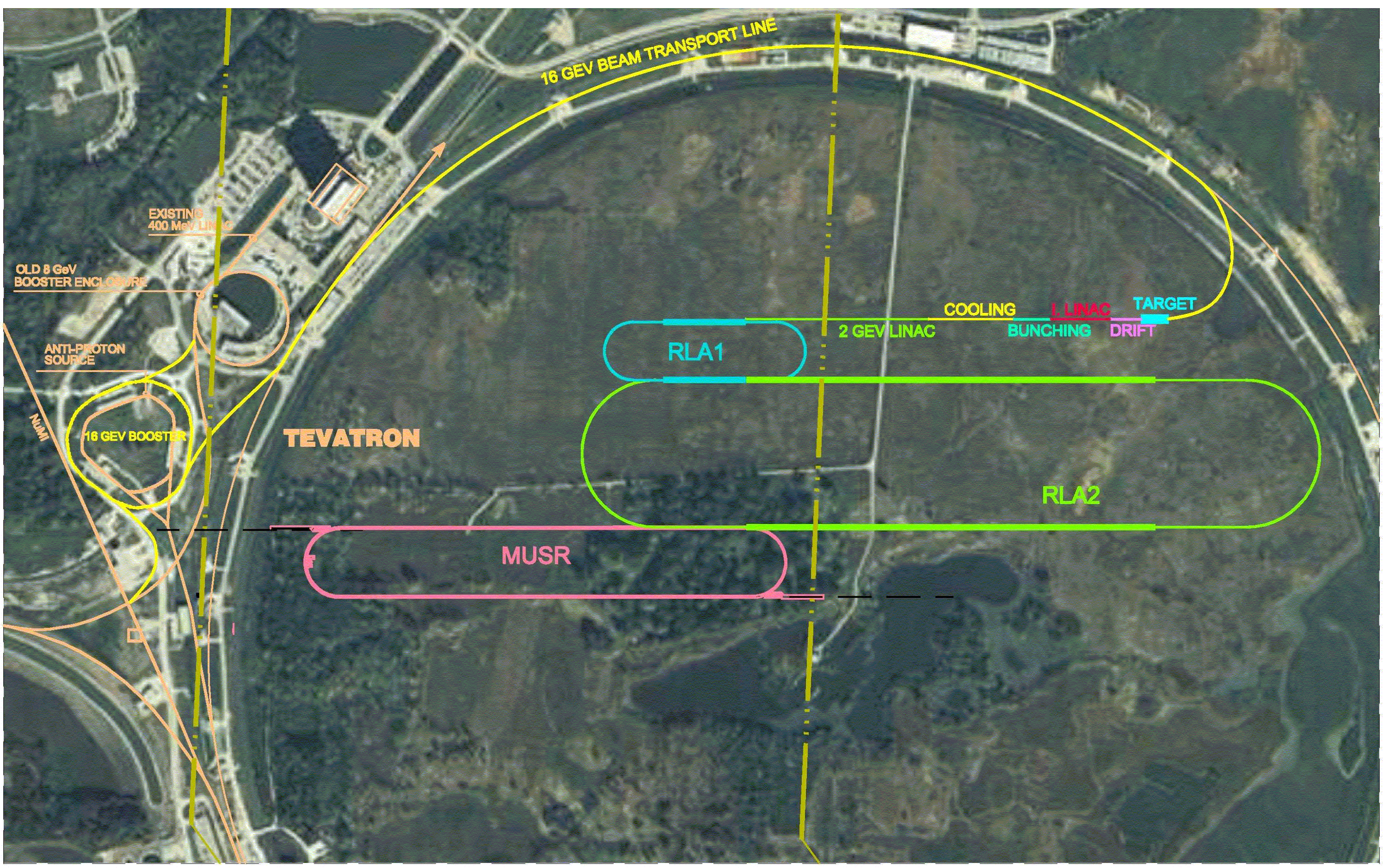
LOCATION HATCH
WETLAND HATCH

LIMITS:	mrem/year	CONTROL CYL.	
CASE 1. 50GeV	10	4.5KM	RADIUS=4.0M
CASE 2. 50GeV	100	1.4KM	RADIUS=1.2M
CASE 3. 30GeV	10	2.5KM	RADIUS=5.0M

MuSR
CTE 15-OCT-99

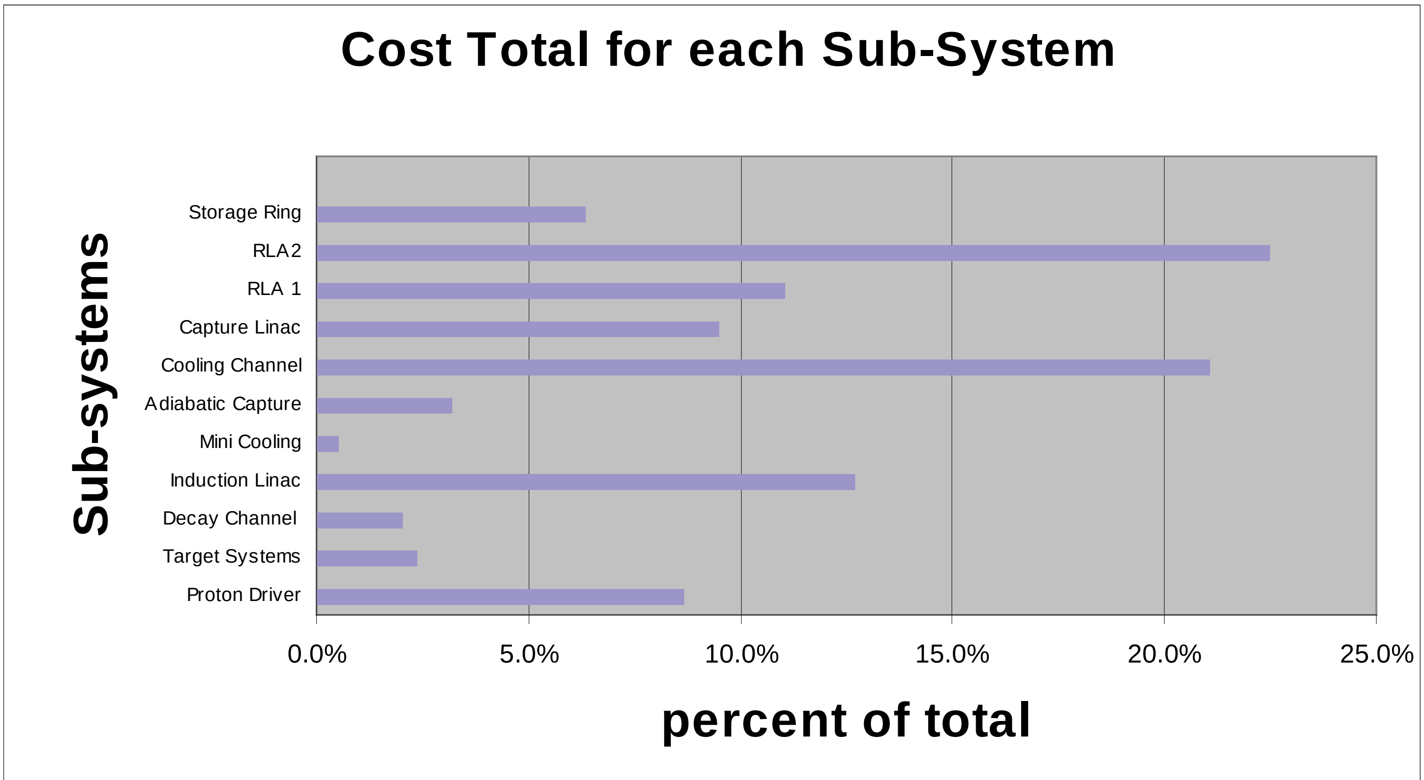
Layout on this Site

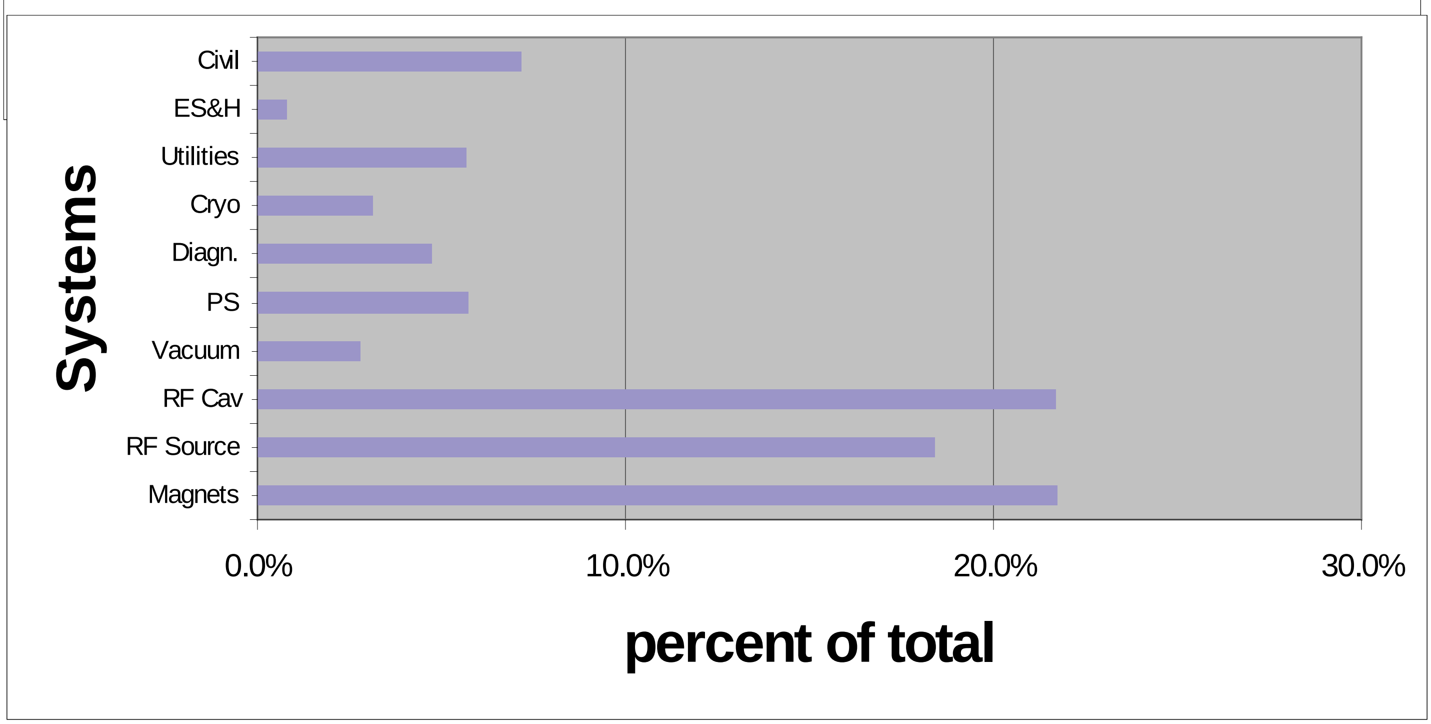
- Why ?
  - Worldwide Unique facility
  - Detector cost and Accelerator cost can be balanced
  - Long Term program ⇒can be staged
  - Fits under a site
  - Has a large NSF/University/Illinois State/Inter Lab. collab



Cost

- Hot Topic: Proposal for Presentation.





Scenarios

- Acceleration is a cost driver
  - no choice with this scenario$\Rightarrow$ limited by transverse cooling we can achieve without emittance exchange
  - emittance exchange (exchange of longitudinal and transverse emittance): no solution available
  - more cooling does not necessarily mean less money
- Two possibilities:
  - stay with this scenario and develop the technology to accelerate this kind of an emittance
    - aggressive R&D program might bring us into a position to have a ZDR in a couple of years (~5)
    - make sure that we doen't exclude further improvements in the cooling
    - start with "minimal" scenario for number of Muons/year
    - may be start without cooling ~ 10^{19} μ/Y
  - go into a longer term R&D program and work on conceptual designs for better cooling channels.
    - No hardware R&D required now
    - shift the ZDR stage an unknown amount of years

Where did we fail?

- Diagnostics:
  - "How do you measure the emittance of the muons in a solenoid with Pions, electrons and protons going down the same channel?" -solenoid- -other charged particles-
  - Resolution: One cooling cell reduces $\varepsilon_{\perp}$ by ~ few % $\rightarrow$ measure at least 1/5th of that
- RLA's:
  - need a lot more attention and is very preliminary
- Acceleration in General:
  - Ever reappearing FFAG
    - Magnets
    - Isochronousity of the lattice or
    - Fast phase shift of high gradient cavities
- Cost:
  - we were not able to bring the cost under 1 Billion for 50 GeV and that intensity
- Power consumption:
  - going to be a >150 MW facility

What did we do good?

- Involvement
  - NF and MC collaboration played a major role after some resistance
  - Universities and NSF became part of this
  - other Laboratories get heavily involved
- Developed concept and demonstrated feasibility
  - staged plan to fit various budget scenarios
  - presented basically a long upgrade route: Program not a project
  - first cut on cost and know how to get it under control

What is the Plan

- R&D Plan for 3 + years ⇒M. Zisman
  - Broad attack on almost any front
  - Diagnostics (Universities, NSF) (more money than CRYO or PS)
  - Simulation FNAL, LBNL, BNL, Universities, NSF
  - Detectors (NSF, Universities) → Balance cost: big detector